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Offshore Platform Technology for Science

Inside Front Cover
Artist's conception of Norsk Hydro's Osberg offshore production platform in the North Sea depicting interactions with the atmospheric, sea surface, and oceanic environments. For a detailed description of numerical captions see commentary by Furnes and Frydenbø. Diagram: Courtesy of Norsk Hydro.

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Offshore Platform Technology for Science

Guest Editors:
Bronson Gardner
Peter Wiebe

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Outside Front Cover
BP Exploration's Amberjack platform located at Mississippi Canyon 109 in 1,030 ft (314 m) of water. Currently, it has simultaneous drilling and production operations. Photo: Jim Kosowski; Courtesy BP Exploration.

Outside Back Cover
A large wave approaching Shell Development Corporation's Fulmar platform in the North Sea on November 24, 1981. The lowest horizontal framing level on the platform is at an elevation of approximately 6 m above mean sea level. Photo: M. Philpot. (See paper by Cooper, Forristall, Hamilton, and Ebbesmeyer.)

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Offshore Platforms: An Opportunity to Contribute to Global Science

INTRODUCTION

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This issue is devoted entirely to the use of offshore platforms for scientific purposes. Offshore platforms have been recognized for their great scientific potential since they were first constructed. In the Gulf of Mexico, scientific studies began as early as 1954, just a few years after the first offshore platforms were installed out of sight of land. Active scientific research continues not only in the Gulf of Mexico but also in offshore sites around the world. Curiously, this extensive research record seems to be a well-kept secret. This special issue of the *Marine Technology Society Journal* documents two important facts: (1) platforms currently provide opportunities for a wide range of scientific research and (2) there is potential for even greater benefit to the scientific and offshore communities by linking data monitoring systems and research capabilities on platforms with international data repositories, such as the Global Ocean Observation System (GOOS) and the International Geosphere-Biosphere Program (IGBP), to create an oceanographic-climatic monitoring network.

PLATFORM RESEARCH EXPERIENCES

Practical Lessons Learned

First and foremost, offshore platforms are essential sites of business for the companies that operate them. Daily operations are affected by strict environmental and safety requirements. In practice, this means that the exploration and production community has a different set of day-to-day priorities than the research community and may not be able to accommodate all research requirements. This means that researchers face a challenge in designing studies that are both scientifically meaningful and that fit within the local operating constraints.

During the last 30 years, major projects undertaken in the Gulf of Mexico have produced important practical lessons for scientists interested in using offshore platforms. These lessons (and the projects) are summarized in the paper by Cooper et al. The commentary by Nittrouer and Wright discusses unique characteristics of platforms for performing research and some of their potential limitations.

It should also be remembered that there are over 300 companies involved in offshore petroleum and natural gas operations just in the Gulf of Mexico. The commentary by Rooney provides interesting insight with regard to research opportunities on platforms from the perspective of a platform operator.

Making Research Easier

One of the concerns offshore companies have is how they can cooperate with researchers without getting bogged down in the details. The paper by Dokken discusses a unique organization, the Flower Gardens Ocean Research Project (FGORP). FGORP was initially organized as a means of promoting research on platforms owned by Mobil Exploration. FGORP has since become an effective interface between academia and industry. FGORP removes many of the practical barriers that often make companies reluctant to participate in research.

Researchers have begun to ask "Is the offshore industry currently collecting any information that scientists might use?" While it is common knowledge the industry collects information to satisfy regulatory requirements, few have considered the potential scientific value of the same information.

Impact of Platforms on Measurements

Scientists need to know what "local effects" platforms will have on their measurements. Naturally, the answer depends on what type of measurements are being made. The paper by Cooper et al. describes physical impacts, such as disturbances of wind profiles, mechanical motion, and sensor locations. Roscigno and Kennicutt describe a Minerals Management Service effort to assess effects on marine organisms of emissions from offshore platforms. Furnes and Frydenbø's commentary summarizes enviromentally important emissions from platforms.

The paper by Lewis shows that offshore platforms can provide significant information for forecasts of severe storms. The paper also discusses practical problems associated with making atmospheric measurements from platforms. His paper is an example of how industry, academia, and government agencies can work cooperatively to achieve significant scientific goals.

PLATFORMS AS CLIMATIC MONITORING STATIONS

The importance of long-term climatic records is well documented. Landbased networks are widely distributed and have become very

important in many ways. The information gained from these stations is used by farmers, sportsmen, and airlines, just to name a few. Modern society would be much different without the existence of these stations.

Recently, ocean scientists have begun to realize that long-term climatic records of the ocean could be equally valuable. They have also realized that offshore platforms represent a unique resource in obtaining these records, since the standard ocean measuring platforms (ships and airplanes) cannot remain in a fixed area for long periods.

In 1989, the Scripps Institution of Oceanography and the Woods Hole Oceanographic Institution convened a workshop of several dozen scientists to discuss the use of offshore platforms (see the article by Wiebe et al.). The workshop concluded that, with few exceptions, current ocean observation capabilities are inadequate for the needs of ongoing research programs. Even satellite sensors are unable to acquire critical information about the ocean's interior. The workshop concluded that a global ocean observing system will be required to understand the ocean, its dynamics, and its role in weather, climate, biogeochemical cycles, and marine ecosystems. Long-term systematic measurements of the ocean were recognized as an essential element of global change research.

The relative lack of long-term ocean climatic records has a major impact in scientific debates. Climate models used to forecast the impact of greenhouse gases depend heavily on calculations of the behavior of the ocean. It is clear that if oceanic calculations are inaccurate (because of insufficient information), then long-range climate forecasts will also be subject to errors. It is also apparent that many key ocean climate parameters can only be measured from stable, offshore locations, such as petroleum and natural gas platforms.

The concept of using offshore platforms to acquire climatic and oceanographic data is new both to the offshore industry and to oceanographers. As several papers in this issue demonstrate, it is a concept that should be pursued since there are potential benefits to all who would be involved in such an effort.

Development of an offshore observational capability would provide the means to record essential biological, physical, and chemical properties of the ocean environment for protracted periods of time and over a broad spectrum of frequencies. Such a capability requires the use of autonomous instruments. There are a number of sensors that can be used in autonomous systems to measure physical attributes of the marine environment. Fewer autonomous sensors exist for measurement of biological and chemical attributes. The papers by Dacey and Cooper and by Taylor et al. describe both the ongoing need for such measurements and the instrumentation being developed to meet the need.

The existence of an offshore climatic network would create possibilities for research that are not possible today. The commentary by Henderson et al. shows that measurements made at platforms could be used to calibrate satellite sensors aimed at the ocean—thus improving the quality of information derived from this source.

Pioneering work on this concept has been conducted at the Conrad Blucher Institute at Corpus Christi State University. The paper by Jeffress et al. provides an overview of this network, which links coastal measurements with offshore measurements into a centralized database. The Texas Coastal Observation Network (TCOON) was originally developed to provide the city of Corpus Christi with water level data during hurricane emergencies. TCOON has now been expanded to include much of the Texas coastal region and several offshore sites. The use of this network in oil spill response, environmental management, and long-term studies of sea-level is described.

At present, the concept of creating an international oceanographic-climatic monitoring system using offshore platforms is still in the discussion stage. Many questions remain unanswered. For example, should there be a standardized instrument package? What parameters should be included? Who would manage the system? How would the network be financed? The commentary by Busch discusses the structure of an overall program, the roles of government and industry, the importance of the program to the private sector, and the international implications.

We hope that this special issue of the *Marine Technology Society Journal* will stimulate interest on this important topic. As the debate about global climate change proceeds, the importance of reliable long time-series information from a global network of offshore stations will become increasingly important. It should revolutionize our understanding of the forces that currently shape the existing marine ecosystems and enable us to assess more critically the consequences of climate change.

Government-Industry Alliance: New Strategy for Environmental Research

PROGRAM OVERVIEW

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ISSUE AND OPPORTUNITY

The use of offshore oil production platforms provides a unique opportunity for conducting environmental research. The efforts toward implementing this capability are a prime example of industry, government, and scientific communities forming an alliance to solve complex environmental problems.

Traditional platforms, such as ships, buoys, and aircraft, used for gathering data from the upper atmosphere, through the air-sea interface, and down to the seafloor, often lack capabilities needed by researchers. Table 1 compares the major characteristics of these systems. They do not normally allow for long time-series measurements (e.g., 10 to 20 years); they are very dependent on weather conditions; they are of limited use in hazardous and remote environments; and they often allow only minimal experimental flexibility. Spacecraft, while offering broad coverage, are also limited since they can only monitor parameters above and on the surface of the ocean but not beneath it. The use of offshore platforms is a new and potentially valuable concept in conducting oceanic and atmospheric research worldwide.

Ultimately, a network of manned research laboratory units that will be placed on offshore platforms and located throughout the world's oceans is envisioned. Using these, researchers could conduct real-time and in situ experiments as well as establish long time-series monitoring networks. These platforms are unique in that they provide a stable facility that is relatively impervious to hostile weather, fixed at a permanent coastal location, and can provide needed space and support. It is planned that the resulting data would be inputted into a worldwide repository network such as the Global Oceanographic Observations System (GOOS) and actively participate in large-scale programs such as those of the International Council of Scientific Unions (ICSU).

IMPORTANCE TO INDUSTRY

This program provides an unparalleled opportunity wherein the private sector, government, and research communities, both domestic and international, can synergistically pool their resources, facilities, and capabilities. It gives the offshore industry direct access to ongoing U.S. government sponsored research programs; its scientists, managers, administrators, policy workers, and decision makers; and interagency coordinating groups that address both policy and scientific issues. This provides industry the ability to influence policy direction and voice opinions, develop channels of communications, and establish links with government counterparts. The credibility gained by both government and industry could then be extrapolated to other areas of partnerships and collaborative activities. In addition, a number of companies have indicated that joint projects of this nature would greatly enhance the public image of the offshore industry regarding environmental issues. Industry already plays a critical role in this area of environmental concern because of its direct and immediate interface with the public. Its role in providing the goods and services needed to address these issues will be further emphasized in the future.

From another perspective, many large companies and multinational corporations are taking an interactive role with society and are not concerned only with profit margins. They are developing the capability of using resources in a realistic and concerned manner, working synergistically with government. For example, the International Chamber of Commerce has developed a charter that provides 16 guidelines that companies should follow related to environmental sustainable development. This has been accepted and supported by a large number (more than 2,000) of international companies.

ONGOING EFFORTS

Until recently few, if any, companies have allowed scientists to have limited access to their offshore facilities. Mobil Oil, working with the Flower Garden Ocean Research Project (FGORP), has opened one of their platforms in the Gulf of Mexico to scientific research teams. The Gulf Offshore Satellite Applications Project (GOSAP) is working with seven oil companies in the Gulf of Mexico to obtain "ground truth" data from oil platforms for calibrating satellite sensors.

Through the collaborative efforts of the Private Enterprise and Government Interaction (PEGI) Working Group of the Federal Coordinating Council for Science, Engineering and Technology's (FCCSET) Committee on Earth and Environmental Sciences (CEES), and the American Petroleum Institute (API), federal agencies have been working closely with BP

TABLE 1. Comparison of sensor platforms for environmental and global change research.

Characteristics	Aircraft	Buoys	Offshore Platforms	Satellites	Ships
Data Quality					
Foul weather date available	No, unless special weather mission	Some	Yes, significant advantage over other methods	Some, atmos. profile & sea surface	Very little
Area coverage	Wide	Limited	Limited	Global	Wide
Range from platform	Wide	Minimal	Wide, using acoustic, hard wire, & optical links and AUVs	Wide	Generally limited depending on sensors
Sensor accuracy and resolution	Good	Good	Good	Good	Good
Number of parameters measured	Many	Few	Many	Few	Many
Data processing	Limited	No	Yes	No	Yes
Impact of system's presence on measurements	Limited	Limited	Potentially yes for close-in activities	No	No
Operations					
Onsite instrument maintenance & logistical support	Limited	None	Excellent	None	Limited (depends on mission of ship)
Available working space	Limited	None	Large	None	Limited
Long-term onsite living & working	None	None	Large	None	Limited
Safety concerns, requirements, & personnel procedures	Limited	None	Very stringent	None	Limited
Auxiliary support craft/systems	None	None	Potentially many (work boats, drive systems, ROVs)	None	Limited
Cost for use of platform	High	Mission dependent	Low	High	Mission dependent
Applications					
Short-term Studies	Yes	Yes	Yes	Yes	Yes
Long-term studies (time series)	None	Limited	Very good (possibly 20-30 years, depending on platform)	Yes, huge amount of data but limited spatially or frequency	Limited (very expensive)
Real-time experimental reconfiguration & change of protocol	None	None	Good	None	Limited
Manned (active scientific participation)	None	None	Good	None	Limited
In situ measurement capability	Yes (atmosphere) No (ocean)	Yes	Yes	Yes (upper atmosphere)	Yes
Research flexibility	Limited	None	Yes	None	Limited
Climate modelling data	Yes	Yes	Very useful	Yes	Yes
Simultaneous atmosphere, sea surface, pelagic, and benthic measurements	No	Limited	Very good	No	Limited
Biological studies	No	No	Very good	No	Yes (short-term)

America to establish a well structured, scientifically credible, and long-range research program. In addition, negotiations to explore the possibilities of working in the North Sea and Arctic regions are ongoing with the National Oceanic and Atmospheric Administration (NOAA), the University of Bergen, Norsk Hydro and the other maritime organizations from Norway, as well as BP International of the United Kingdom. All of those involved are enthusiastic about this program's potential for the science community and their industry.

RESEARCH OPPORTUNITIES

In November 1989 a workshop entitled "Deep Sea Observations" was held in Washington, D.C. to address the new scientific opportunities available by using these platforms. A multidisciplinary approach was taken wherein specialists in oceanographic and climatic research and development participated. The findings of this workshop provided a basis for developing a new long-range program to address scientific areas that include:

1. Frequency spectra of marine ecosystem variables,
2. Biogeochemical processes, the carbon cycle, and new primary production,
3. Coupled ocean-atmosphere systems, interactions, and energy transfers,
4. Physical oceanographic processes and systems from sea surface to seafloor, and
5. Meteorological and climate processes and systems.

Specific measurements that researchers would like to make from platforms are outlined in Table 2. Initially, pilot projects using automated systems requiring no operational support from the platform will be conducted for feasibility demonstration. Ideally, calibrated systems could be installed on platforms in areas of the North Sea, the Gulf of Mexico, and the tropical South Pacific to monitor the same parameters at each site for comparative studies.

The artists' conceptual drawing on the back inside cover of this issue provides a good perspective of the range of research and monitoring possibilities available by using a platform as a base of operations. An important concern is the platform's presence having a possible impact on the measurements. Studies have to be conducted to determine how this potential effect can be minimized and/or accounted for. In addition, data can be taken remotely using instruments placed at distances from the platform with acoustic, optical, and/or hard wire data links back to the platform.

Companies have also suggested that their work boats supporting the platform operations

TABLE 2. Proposed time-series measurements that are desirable from offshore platforms.

Automatic/Remote (Requiring No Operational Support)

High Frequency Observations and Measurements (Daily/Continuous)

Physics (Atmosphere)
- Outgoing long-wave radiation
- Wind speed and direction
- Relative humidity
- Barometric pressure
- Surface air temperature
- Light 0.3 to 3μm

Physics (Ocean)
- Wave conditions
- Sea surface temperature
- Conductivity, temperature, depth (0-1,000 m)
- Currents (0-200 m; acoustic profiling of ocean currents, or APOC)
- Submarine light to less than 0.1% of surface illumination

Chemistry
- Dissolved nutrients: NO_3, NO_2, NH_4, UREA, SIO_4, PO_4 (0-500 m)

Biology
- Chlorophyll profile (plus phaeopigments)
- Macrozooplankton carbon: (0-1,000 m including euphotic zone)
- Micronekton by acoustics
- Primary production (to a water depth representing 0.1% light)

Real-Time Analysis (Requiring Manned Support)

High Frequency Observations and Measurements (Daily/Continuous)

Physics (Ocean)
- Currents (greater than 200 m)

Chemistry
- Total CO_2 alkalinity, $_pCO_2$
- O_2

Biology
- Microbial carbon (in euphotic zone)
- Phytoplankton carbon (in euphotic zone)
- Microzooplankton carbon (euphotic zone plus integrated 0-1,000 m)
- Size frequency distributions of living matter (euphotic zone)

Low Frequency (Weekly-Monthly)

Physics (Ocean)
- Lagrangian currents (drifters)
- Deep conductivity-temperature-depth (CTD) casts (0-2,000 m)
- Deep currents (moorings)

Chemistry
- Argon, ^{3}He particulate organic carbon (POC), nitrogen (PON), phosphorous (POP), and silicon (PSI), (0-2,000 m)
- Dissolved organic carbon (DOC), nitrogen (DON), and phosphorous (DOP)
- Dissolved nutrients (0-2,000 m)
- Deep total CO_2, alkalinity, $_pCO_2$
- Sinking particles (traps-upper 2,000 m)

Biology
- Depth stratified sampling for all size categories (day/night to 1,000 m)
- Replicate water column primary production (three-to-four per depth per day biweekly)

Additional Proposed Measurements

Radiation (UV, radiance, downwelling light)
Particulate Deposition
Rainfall
Water Column Currents
Transmisivity
Flourometery (measuring flouresense)
Temp, Salinity

Biomass (acouticalls, standing crop & turn-off rates, plankton particle counter)
Nutrients (nitrate, phosphate, O_2, silicates)
Photosynthetic Rate (primary production)
Zooplankton Biomass
Acoustic Measurements (tomographic techniques and Doppler systems)
Dimethal Sulphide (DMS)

could at times, on a non-interference basis, be used for research activities. In addition, companies have indicated that their terrestrial based sites could also be used by scientists. Many of these are located in areas of high interest to researchers, such as deserts, the arctic and antarctic, the tropics, and rain forests. Interest has also been shown in placing working labs on weather ships stationed in the North Atlantic.

Each company monitors certain environmental parameters on their platforms regularly and in many instances continuously for operational needs. They are also often required to have extensive environmental surveys of the areas surrounding the platform conducted periodically (i.e., every one to three years). This data, some of which may go back to the early 1970s, can be made available to the science community as needed. The information may be comprehensive for operational needs but not necessarily sufficient for scientific use. It could, however, prove very useful for future planning of environmental activities and installations.

INTERNATIONAL ASPECTS

The international importance of this program is exemplified by the enthusiastic support of international and domestic offshore companies and the strong interest shown by researchers involved with large multi-nation scientific organizations, such as ICSU, the International Oceanographic Committee (IOC), and the World Meteorological Organization (WMO) that sponsor programs such as the International Geoscience Biosphere Project (IGBP) and the Joint Global Ocean Flux Study (JGOFS) programs. IGBP's Land Ocean Interaction with the Coastal Zone (LOICZ) program is studying near shore areas within normal locations of platforms. Note that JGOFS presently operates stations at Hawaii and Bermuda making long-term time series measurements of oceanographic and atmospheric data. Offshore platforms would provide optimal bases from which they could expand the number of JGOFS measurement sites providing better coverage of the oceans. In addition to using GOOS as a network for disseminating data from platforms, the GOOS Health of the Oceans program would directly benefit from access to specific platforms.

PROGRAM STRUCTURE

Instead of establishing a program on an ad hoc and case-by-case basis, a long-term, well structured, and unbiased research program is envisioned based on meritorious science. While industry and the science community both have specific roles, they also would be full partners involved in all aspects of planning, solicitation, peer review, selection, implementation, and sharing of results as shown in Figure 1. Extensive negotiations have already been held with industry. It is agreed that the operations managers of the respective offshore platforms being used would have the final say and approval of given projects considered for selection based on safety, security, logistics, installation, and any other factors they consider critical. This relationship will be a true partnership based on specific guidelines and criteria agreed to beforehand.

FUNDING AND SUPPORT

As always, the practical question of funding is a major concern. The ideal solution, of course, is for a government source of support to be identified. However, in today's climate of fiscal constraint and downsizing, support is not readily available. This does not preclude researchers from submitting proposals that include the use of platforms to traditional funding agencies such as the National Science Foundation, Office of Naval Research, and other groups appropriate to their areas of interest. Private sector groups and industry could also provide support in their areas of focus.

An "Announcement of Opportunity" should be sent to the science community worldwide, describing the program, its opportunities, potential platforms, and oceanic areas. This would allow scientists to consider the advantages of using a platform and submit research proposals to potential funding sources.

The use of offshore platforms would expand and complement the progress of many programs that are ongoing and already funded. Individuals working with these programs, particularly those in coastal areas, should consider the unique advantages of using these platforms.

SUMMARY

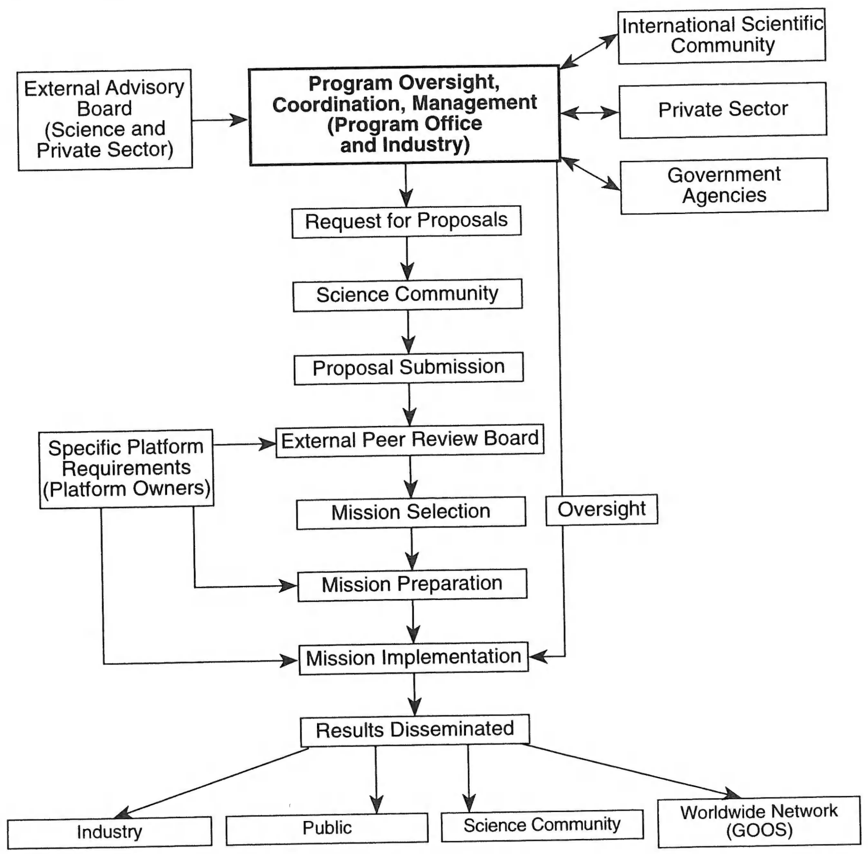
Although there is intense environmental and scientific interest to work in and obtain long-term data sets from given areas in the arctic (Barents and Kara Seas), little is being done except for some limited oceanographic ship missions. Russian companies and government organizations are planning to place two platforms in these areas (approximately 73°N) by the year 1997 and 2000, respectively. Now is a golden opportunity for researchers to have a permanent laboratory facility designed into these systems during construction.

Industry has indicated that designs are currently underway for offshore platforms that will work in deep water depths beyond the continental shelf areas. This may provide a good opportunity for the industry and science communities to specify what should be included in the design, such as the parameters to be monitored, the special facilities or equipment needed, and specific subsea mounting requirements. Looking toward the future, the research community needs an independent semi-submersible type platform that can operate at any water depths for long-term observations. This program will provide the basis and experience for developing such systems.

The use of platforms allows long-term monitoring capabilities in specific locations and under hazardous conditions. It also provides a unique opportunity where the research communities and private sectors, both domestic and international, can work synergistically. In addition, their use will allow government institutions, such as the United Nations, to include this data and information, as appropriate, in international efforts and decision-making processes, especially those environmentally related and having global implications.

These new and non-traditional research stations will play significant roles in future marine research. They have the ability to redefine the previous and preferred methods of studying the oceans.

FIGURE 1. Framework for a long-term research program using offshore platforms.



PAPER

Utilization of Offshore Oil Platforms for Meteorological and Oceanographic Measurements

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ABSTRACT

Meteorologic and oceanographic (metocean) data, obtained from instrumented offshore oil platforms over the past three decades, are presented with summaries of major projects devoted to winds, surface gravity waves, wind and tidal current velocities, eddies, and internal waves. Advantages and limitations of working from platforms are described in terms of practical aspects. In addition we briefly describe an inexpensive and reliable metocean measurement system which has recently evolved based on lessons learned.

INTRODUCTION

Offshore oil platforms provide convenient, cost-effective locations for making long-term meteorological and oceanographic (metocean) measurements. Though most marine scientists are not familiar with these platforms, several major projects have been conducted and many practical lessons learned during the past three decades (Table 1). Many of these projects were motivated by the need to measure processes that generate large forces on offshore oil or gas producing facilities. Consequently, the projects focused on measurements of surface gravity waves, currents, winds, and surges driven by tropical and extratropical storms (Forristall, 1992).

Scientists, who previously had to rely on moorings, found platforms very useful, though with limitations. Since these limitations are common to most platforms, specific techniques and instrumentation for dealing with them have evolved.

Historically, a jacket-type platform (i.e., a 4-to-8 legged tubular structure, held in place by piles driven into the seafloor) was the type usually used by scientists. More recently, six types of platforms have been commonly used (Figure 1). These platforms share much the same processing equipment, thereby enabling the evolution of a generic type of metocean system described in the last section of this paper.

The procedures described in this paper represent the experience of the authors in the Gulf of Mexico, the North Sea, and the South China Sea. This paper contains three sections: major metocean projects conducted from offshore oil platforms, advantages and limitations of offshore platforms for research, and a generic system for metocean measurements.

MAJOR METOCEAN PROJECTS CONDUCTED FROM OFFSHORE OIL PLATFORMS

Platform Responses

The first major efforts to obtain environmental measurements from offshore platforms were Wave Force Projects I and II (Table 1). Two Gulf of Mexico platforms in 10 and 30 m of water were instrumented with strain gauges and metocean sensors and were operated from 1958 to 1963 (Russell et al., 1966; Thrasher and Aagaard, 1969).

Ohmart and Gratz (1978) measured platform response, metocean inputs, and wave kinematics from a platform in 50 m depth off Louisiana. As the oil industry has moved to deeper water, more extensive projects have been conducted. For example, Ebbesmeyer et al. (1982), Marshall et al. (1983), and Forristall et al. (1989) reported on data taken from the Cognac jacket in 312 m off Louisiana. The instrumentation included on the first guyed tower, Lena, off Louisiana was documented by Lamb et al. (1984).

Peters et al. (1990) described instrumentation on the deepest platform to date, the Jolliet tension-leg platform (TLP) in 600 m off the western Louisiana coast. An extensive study was carried out on the Hermosa platform in 200 m off Pt. Arguello, California, by Mason et al. (1992). The Tern platform in the North Sea was extensively instrumented (Heideman and Weaver, 1992).

The ocean test structure (OTS) was the only platform deployed by the oil industry devoted solely to the examination of metocean forces on offshore facilities (Geminder and Pomonik, 1979). A complete set of force sensors and strain gauges, as well as five wave staffs, 11 electromagnetic current meters, an anemometer, a barometer, a thermometer and one of the first digital recorders were placed on the OTS. The OTS was located in 20 m of water off Louisiana from 1976 to 1978, and measurements included those obtained in two severe winter storms and hurricane Anita.

Ocean Data Gathering Program (ODGP)

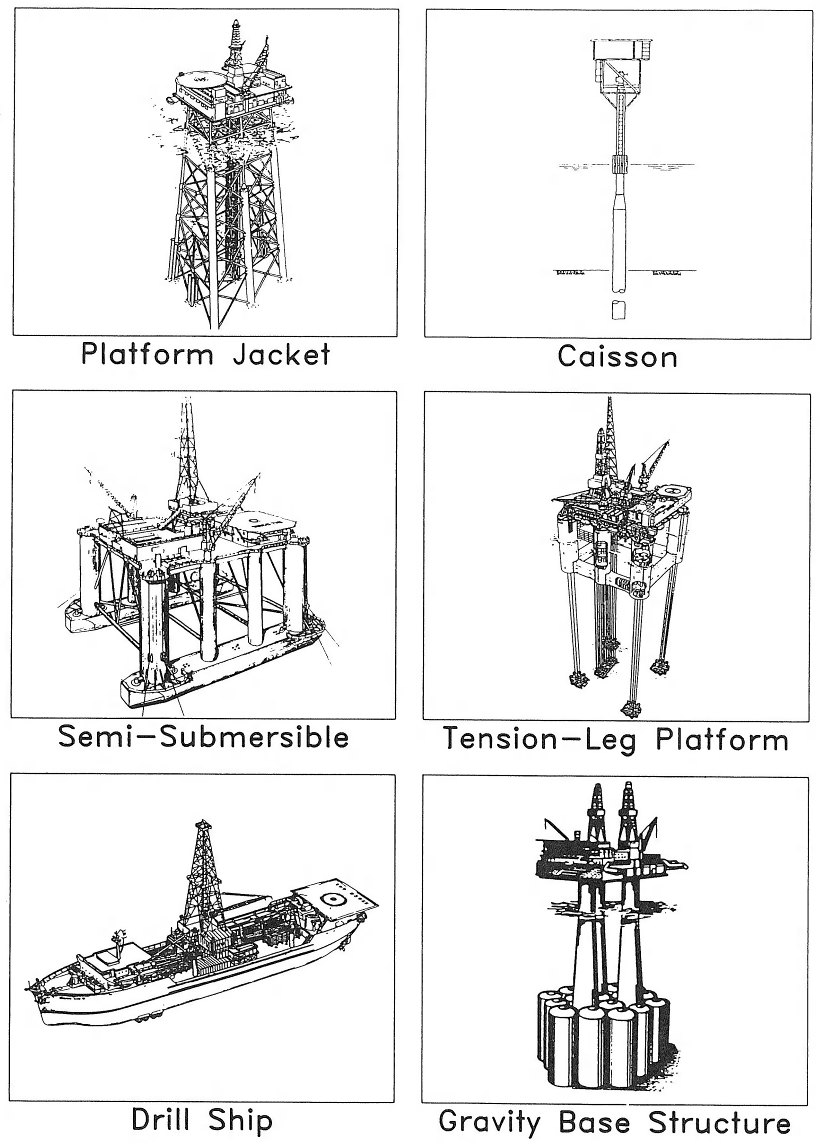
Although the ODGP was completed 20 years ago, it remains the most extensive data collection conducted by the oil industry. As oil production moved to deeper water in the late 1960s, hurricane waves posed the dominant threat to offshore structures. More information about these waves was required. The ODGP marked the first use of the Baylor wave staff, an accurate and reliable device that has become a standard component in many subsequent wave studies.

The ODGP began in October 1968 and continued for three years. To improve the probability of measuring large hurricane waves, six platforms were instrumented with wave staffs, anemometers, and barometers (Patterson, 1969; Hamilton and Ward, 1974; and Ward, 1974). The platforms were located off the Louisiana coast in water depths of 25 to 100 m. The most significant data were measured in 1969 during hurricane Camille. A 72-ft wave (22 m), measured at one platform, was much larger than approximately 55 ft (17 m), the standard design wave at

TABLE 1. Summary of major metocean projects.

Program	Number of Platforms and Locations	Platform Latitude and Longitude	Measurements Taken	Period of Program
WAVE FORCE I WAVE FORCE II	2, Gulf of Mexico	29.25 N, 90.25 W 28.83 N, 90.25 W	Wave forces, waves	1954 - 1958 1960 - 1963
ODGP	6, Gulf of Mexico	29.1 N, 88.7 W 28.8 N, 89.7 W 28.5 N, 90.4 W 28.3 N, 91.2 W 28.7 N, 91.9 W 28.9 N, 92.7 W	Wind, barometric pressure, waves	10/68 - 11/1971
OCMP	3, Gulf of Mexico	28.9 N, 94.7 W 28.2 N, 91.7 W 29.1 N, 88.7 W	Wind, barometric pressure, currents, particle velocities	1971 - 1977
OTS	1, Gulf of Mexico	28.8 N, 90.4 W	Waves, currents, particle velocities, crest velocities, wave forces, wind, barometric pressure, temperature	1976 - 1978
FULWACK	1, North Sea	56.4 N, 2.1 E	Waves, currents, particle velocities, crest velocities, wind	1981-1982
BULLWINKLE	1, Gulf of Mexico	27.9 N, 90.9 W	Waves, currents, particle velocities, crest velocities, wind, barometric pressure, temperature (air and sea), accelerations, strains	1989- present
SWAMP	1, Gulf of Mexico	29.0 N, 89.3 W	Waves, currents, particle velocities, wind, bottom pressures, bottom motion	1979-1981
WADIC	1, North Sea	56.47 N, 3.1 E	Waves, currents	1985 - 1986
CUMEX	1, North Sea	61.0 N, 1.0 E	Waves, currents, particle velocities, temperature profiles, wind, conductivity	1984 - 1987
Baseline Metocean Studies	Various, North Sea Various, Canadian East Coast Several, Nigeria South China Sea	Various	Waves, currents, winds, particle velocities, tides, barometric pressure, temperature, humidity	1967- present
Deepwater Current Measurements	Various, Gulf of Mexico 2, South China Sea Andaman Sea Shetland Islands	Various	Current profiles, surface currents, water temperature	1981-present
GMAQS	3, Gulf of Mexico	29.1 N, 93.2 W 28.9 N, 91.3 W 27.2 N, 91.4 W	Upper air velocity, upper air temperature, surface wind, barometric pressure, surface temperature, rainfall, telemetry	April - Oct. 1993
MOMS	4, Gulf of Mexico	27.9 N, 90.9 W 27.8 N, 93.1 W 28.2 N, 89.1 W 29.4 N, 88.6 W	Waves, currents, barometric pressure, air temperature, telemetry	1989-1992

FIGURE 1. Six types of offshore platforms from which major metocean projects have been conducted: jacket, caisson, semi-submersible, tension-leg platform, drill ship, and gravity base structure.



the time. As a result, offshore operators in the Gulf of Mexico increased their platform design criteria. The time series containing the 72-ft wave may well be the most intensely studied and influential wave ever recorded by metocean instrumentation (Figure 2).

The data obtained during hurricane Camille and other storms were used in reevaluating theories of the probability of the occurrence of waves during extreme events (Earle et al., 1974; Earle, 1975; Haring et al., 1976). The data were also used to develop hurricane wave prediction models for use in the design of offshore platforms (Ward et al., 1978; Haring and Heideman, 1978).

Ocean Current Measuring Program (OCMP)

The OCMP was the first extensive study of hurricane-generated currents. The introduction of electromagnetic current meters and the availability of fixed platforms as mounting sites made such measurements possible in the presence of large waves.

From 1971 to 1977, three platforms were instrumented and maintained off Louisiana in depths of 20 to 100 m. Data were recorded during tropical storm Delia (1972) and hurricanes Carmen (1974), Eloise (1977), Anita (1977), and Babe (1977). These data, together with measurements during other storms, have been used to calibrate numerical models of hurricane currents (Forristall et al., 1977; Cooper and Thompson, 1989). The response time of the electromagnetic current meters and the recording system were sufficiently rapid to resolve adequately wave orbital velocities; therefore, it was also possible to examine wave kinematics and directional spectra.

Fulmar Wave Crest Kinematics Experiment (FULWACK)

Offshore platforms have been used for studying wave kinematics near the sea surface. FULWACK, one of the most ambitious projects to date, operated during winter, 1981-1982. Five electromagnetic current meters were mounted on the Fulmar platform (82 m depth) in the North Sea at elevations up to 8 m above mean sea level. In November 1981, a gale produced several waves that inundated the uppermost current meter. One of the waves was photographed by M. Philpot from a semi-submersible moored near Fulmar (see outside back cover of this issue).

Many studies of wave kinematics have been reported. Forristall (1986) found that linear wave theories systematically overpredicted orbital velocities in the wave crests, as well as below mean sea level. Ohmart and Gratz (1978) analyzed data from a jacket structure in the Gulf of Mexico, and data from the OTS electromagnetic current meters mounted above mean sea level were used by Dean et al. (1979) for their study. Measurements from two electromagnetic current meters and a pressure transducer on a tower in 16 m depth in the northern Adriatic Sea were analyzed by Cavaleri et al. (1977). Battjes and van Heteren (1984) used acoustic sensors and a wave staff to make measurements from the Noordwijk platform in 17 m depth in the southern North Sea. Much later, Drennan et al. (1992) analyzed data from miniature drag spheres and ten wave staffs on a platform in 13 m depth, maintained by the Canadian National Water Research Institute in Lake Ontario. These

Italian, Dutch, and Canadian platforms are all dedicated to oceanographic and meteorological research, which offers considerable advantages in access to the platform and flexibility of siting instruments compared to the use of platforms that were built for other purposes. For example, since the Canadian platform was designed for wave measurements, it is completely free of cross bracing near the water surface. Instruments on the Noordwijk platform are mounted on fairly transparent space frames which are attached outboard of the 0.8 m platform legs. The frames can be lifted out of the water for inspection or cleaning of the sensors.

Bullwinkle Instrumentation

The only extensive study of platform blockage of winds, waves, and currents was conducted from the Bullwinkle jacket platform in 410 m depth off Louisiana. The instrumentation was described by Swanson and Baxter (1989). Anemometers were installed on both drilling derricks, wave staffs were placed on two opposite corners of the structure, and two acoustic Doppler current profilers (ADCPs) were arranged so that a total of eight ADCP beams were directed outward from the platform in a single depth range. The most severe storm sampled to date was hurricane Andrew in August 1992.

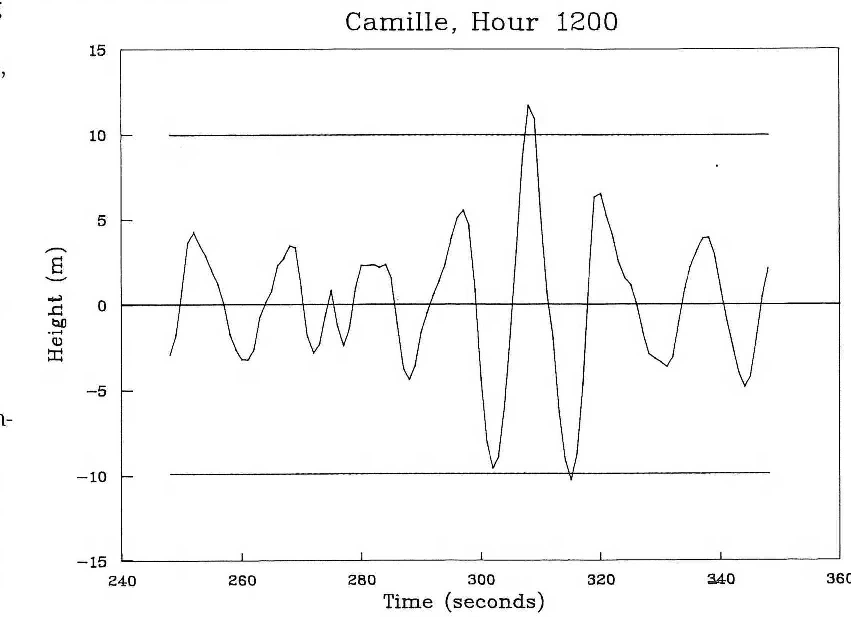
The Sea Wave Attenuation Measurement Project (SWAMP)

The SWAMP was designed to examine attenuation of surface gravity waves by the motion of a soft seafloor at two Gulf of Mexico locations: a deep-water station (312 m) at Cognac and a shallow water station on Platform VV in 19 m depth. The oceanographic instruments were mounted on a mast suspended from a 60 m-long bridge at VV. This location minimized interference of the waves and mud motion by the platforms. The instrumentation consisted of a wave staff, two current meters, an anemometer, a pressure gauge near the seafloor, and a ballasted float at the end of a pivoted arm used to measure the motion of the bottom with respect to the mast. Forristall and Reece (1985), who examined seven storms (1979-1981), concluded that a nonlinear wave attenuation mechanism became increasingly strong as wave heights increased.

Wave Direction Measurement Calibration Project (WADIC)

A comprehensive field trial of most commercially available directional wave measurement systems was conducted from a jacket platform in the North Sea. Instruments tested included seven buoys, a current and wave staff triplet, a pentagonal array of downward-looking

FIGURE 2. The largest wave recorded during Hurricane Camille (1969). The significant wave height during the hour in which the wave was recorded was 9.9 m and the distance from crest to trough of the largest wave equalled 22 m (72 ft).



laser sensors, and a radar. In a summary of WADIC results, Allender et al. (1989) noted that most of the systems returned good quality data and were reliable (for the 2-to-3 month period that each system was deployed). Measurement differences were minimal for important engineering parameters, including significant wave height and period and wave direction at the wave spectral peak. However, substantial differences were found during swell, high frequency waves (0.2-0.5 Hz), and high sea states.

Current Measurement Experiment (CUMEX)

The primary goal of CUMEX was to investigate the long-standing disagreement as to whether storm-generated currents are slab-like (constant with depth) or sheared (vary with depth). CUMEX was conducted from a jacket platform in the Norwegian Sea during the winters of 1984-1987. Four horizontal-looking ADCPs and two thermistor strings were mounted on jacket legs at depths of 14, 28, and 71 m; the water depth was approximately 90 m. Aiming the ADCPs horizontally provided a unique set of data that had no appreciable measurement error due to local interference or mooring motion. The most challenging problem was the removal of spurious data from the ADCP, apparently caused by signal reflections from schools of fish.

Results from analyses of twelve severe storms showed that the current profile associated with the storms was slab-like during severe storms (velocity gradient $<3 \times 10^{-4} s^{-1}$). This finding refuted then existing standards in the North and Norwegian seas which dictated substantial current shear. Vyas et al. (1988) showed that the results could be used to reduce the maximum force used in the design of jacket platforms by 25 percent. They concluded that their findings apply to sites where the water column is well-mixed from the sea surface to the seafloor.

Baseline Metocean Studies

Numerous projects involving long-term data collection from offshore platforms have been established, primarily to estimate criteria for designing new platforms. Projects include data collected off Nova Scotia, Canada (Seaconsult, Inc., 1985) and data collected off Nigeria, reported by Mobil (personal communication, D. Szabo, Mobil Research and Development, Dallas, Texas) and Shell (personal communication, C. Shaw, Royal Dutch Shell, the Hague, Netherlands) oil companies. The AGIP, Chevron, and Texaco (ACT) group has an ongoing project from a jacket platform in 100 m depth in the South China Sea. By far the most intensively sampled areas are in the North and Norwegian seas (Marex, 1980, 1986a, 1986b; Sand et al., 1990).

Deep Water Current Measurement Complications

As petroleum drilling and production moved to deeper water and diverse geographic regions (greater than 300 m), platform designs became more sensitive to currents. Extensive measurements have been taken over the past decade, primarily from drilling rigs operating in remote areas. Data acquired in summer 1989, when a large eddy, approximately 300 km in diameter, detached from the Loop Current in the eastern Gulf of Mexico, were summarized by Ebbesmeyer et al. (1992) and Glenn and Ebbesmeyer (1993). These currents, reaching 7.4 kph, caused industry losses on the order of $10 million.

Internal waves in the form of solitons also have caused difficulties at a few locations. Strong currents were reported by Osborne and Burch (1980) in the Andaman Sea. In the South China Sea currents of 7.4 kph were observed in solitons, and satellite images traced solitons to a 5 kilometer-wide channel, approximately 500 km east of the site (Ebbesmeyer et al., 1991). Strong tidal currents apparently were responsible for generating the solitons.

Continental shelf waves also have caused problems for offshore drilling operations. Measurements from an extremely active region on the continental slope west of the Shetland Islands showed that currents in shelf waves frequently exceeded 3.7 kph (Hayes Space Technology, 1986).

Wind Profiles

Wind profiles were measured on the West Sole platform in the North Sea by two sets of fast-response anemometers that were mounted at seven levels between 13 and 85 m above mean water level on two sides of the platform's radio tower (Wills, 1982). Brown and Swail (1991) made extensive analyses of wind profiles and associated spectra measured off Nova Scotia. Recently, the Minerals Management Service (MMS) began a study of upper air circulation over the Gulf of Mexico in cooperation with the petroleum industry. The study known as the Gulf of Mexico Air Quality Study (GMAQS) uses radar profilers (based on the Doppler principle), located on offshore platforms, to measure air velocity and temperature to altitudes of 4,500 m and 1,500 m, respectively. The data will be obtained hourly and transmitted by telephone to shore, where it will be combined with data from onshore sites to provide input for numerical modeling of coastal atmospheric conditions. Rawinsondes also will be deployed from an offshore platform for six weeks during summer, 1993, to augment radar profiler measurements and other data obtained by aircraft during periods when high ozone concentrations over land are anticipated.

Metocean Monitoring System (MOMS)

The most extensive cooperative, real-time data collection effort in U.S. waters between the government and the oil industry is a three-year program begun in 1989 called MOMS. The goals were to gather high-quality offshore real-time weather data that would aid government hurricane forecasters, gather data to guide platform operations, and measure extreme conditions, particularly during hurricanes. Four Gulf of Mexico platforms were equipped with a basic suite of instruments to measure currents, waves, winds, air pressure, and temperature. The data were then satellite-telemetered near real-time to the National Weather Service (NWS).

ADVANTAGES AND LIMITATIONS OF OFFSHORE PLATFORMS FOR RESEARCH

Offshore oil platforms provide some distinct advantages, as well as a number of disadvantages for research work. Two of the disadvantages, flow interference and platform motion, are addressed in some detail because they may seriously contaminate the measurements.

Advantages of Working from Offshore Platforms

Sensor mounting. The most obvious advantage is the presence of fixed mounting locations, both above and below the sea surface, which eliminate most requirements for moored systems.

Power. Ample power on the platforms allows use of powerful sensors, as well as reducing the cost of battery packs.

Protection. Platforms provide protection for instruments from trawlers, long liners, and other vessels. Additionally, offshore platforms provide considerable safety for nearby instruments. For example, Gulf of Mexico shrimpers almost invariably trawl up moorings within days after placement, even if they are protected by witness buoys. Therefore, it is a routine practice to place current meter moorings close to platforms for protection.

Logistics and maintenance. Measurement systems are maintained and calibrated more easily on platforms, since a facility is at hand for the storage of expendables and spares and existing transportation often is available.

Personnel assistance. Personnel on platforms may provide some routine maintenance and notification to scientists when problems occur.

Communications. Platforms provide telecommunication links that allow data to be retrieved and viewed routinely from shore, reducing data loss by alerting scientists to problems in a timely fashion.

Limitations of Working from Offshore Platforms

Platform activities. Petroleum-related work on platforms can often damage cables, coat sensors with drilling mud, shield the sensors, generate electrical interference, and cause power failure. Activities having a higher priority for the platforms' owners also may prevent scientists from performing necessary work at specified times.

Personnel activities. Off-duty activities of platform personnel may accidently cause problems with instrumentation, such as cables damaged by fishhooks, power supplies switched off, antennas pointed in the wrong direction by someone seeking to improve TV reception, and computers diverted from data collection to run games. Additionally, offshore platforms act as artificial reefs, attracting many fish; thus, they also attract fishermen with the potential of damaging or fouling sensors.

Power. Although platform power is generally stable and clean, it may contain severe spikes caused by starting large equipment. Additionally, power can inadvertently be lost for short periods of time due to generator problems, or for longer periods, due to platform evacuation during severe weather.

Classification. Some locations on a platform, and some entire platforms, require intrinsically safe instruments and/or explosion-proof housings. Additionally, explosion-proof junction boxes and cables are often required. These requirements may add considerable cost to a project, delay it, or make implementation difficult, due to lack of instrument certification and difficulties in obtaining approved equipment. Furthermore, the restrictions may limit sensor location to unclassified areas that may not be optimal for scientific purposes. It is important to assess and plan for these problems early in the design of a project.

Marine growth. Marine growth can foul sensors, especially current meters, rendering them inaccurate within several months. It can also attract animals that eat the growth, thereby damaging the sensors (e.g., the electrodes of electromagnetic sensors). Growth may complicate retrieval of underwater sensors.

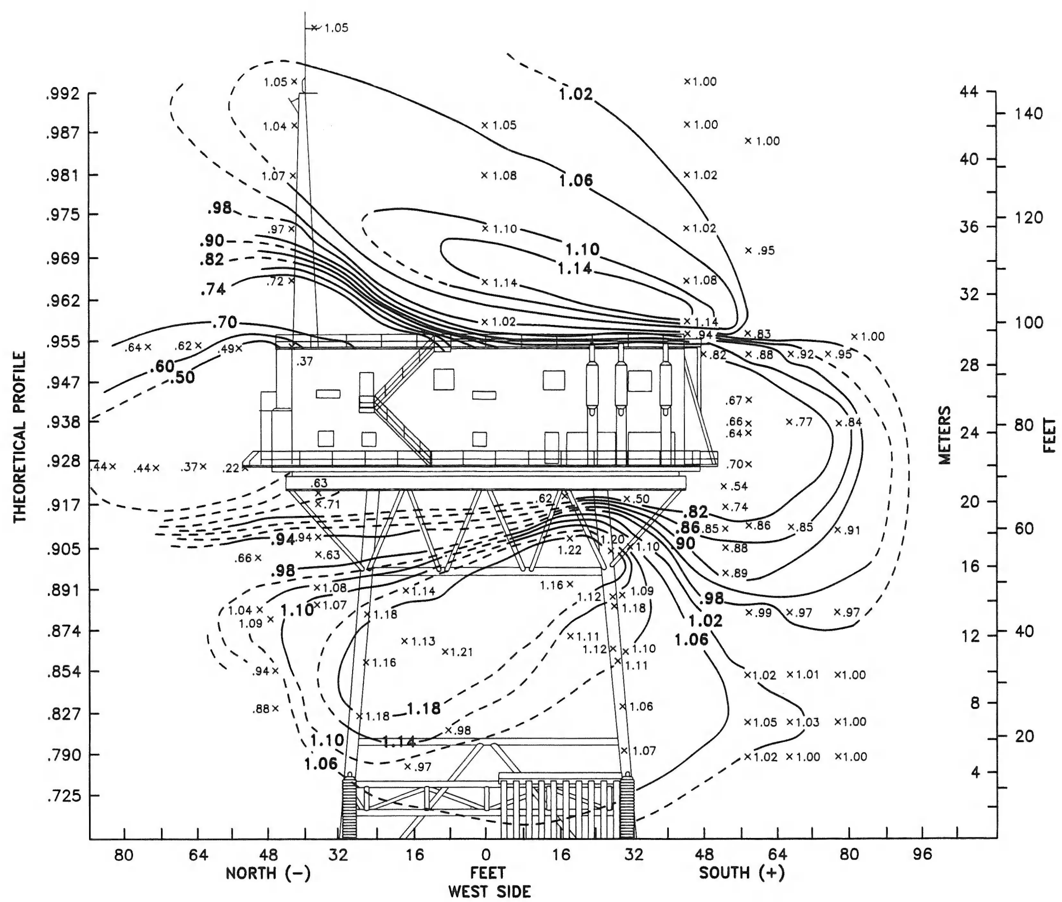
Disturbances Caused by Offshore Platforms

Offshore platforms offer fixed locations for placing instruments in the turbulent ocean, but they also produce substantial disturbance to the flow of both air and water. It is important to recognize these effects both in siting instruments and in interpreting measurements.

Winds

Argus Island, an oceanographic research platform, was constructed by the Naval Oceanographic Office near Bermuda in 60 m depth. A thorough investigation of wind disturbance by the Argus Island tower was carried out by Thornthwaite et al. (1965), who used a movable mast with cup anemometers to map wind speed field around the tower during the summer and fall of 1962. In their map for southerly flow (Figure 3), contours show ratios of measured wind speed at a given location to the undisturbed wind speed at that height above the sea surface. Wind speed was substantially reduced both upstream and downstream by the large building on the platform, and jets of higher speed were apparent above and below the building. Although measurements could not be made far enough downstream to establish the full extent of the disturbance, there was measurable disturbance at 48 m on the north end of the platform.

FIGURE 3. Disturbed airflow around Argus Island for southerly flow expressed as the ratio of observed to undisturbed wind speeds (adapted from Thornthwaite et al., 1965).



As it is difficult to find a good site for an anemometer on platforms, many measurements have been compromised by poor exposure. During hurricane Camille (1969), the anemometer at ODGP Station 1 was located only 2 m above the platform's quarters building, and the wind speed readings were clearly too low. Fortunately at that time, the Transworld Rig 50 was located at about the same relative position to the hurricane's eye, and the anemometer there had a reasonable exposure 34 m above mean water level and 14 m above the rig's hull. The maximum sustained wind speed of 210 kph and maximum gust of 278 kph estimated by J. Bole (Amoco) from the chart recording there played an important role in the development of the hurricane wind and wave models (Cardone et al., 1976).

Ideally, wind measurements should be made at a standard height (e.g., 10 m above the sea surface), but given actual flow disturbances, it appears best to place the anemometer at the highest practical location, typically atop the drilling derrick or microwave tower. The wind speed then may be corrected to a standard elevation, using an accepted expression for the vertical profile.

Currents

The platform's structural members located below the sea surface are not nearly as large as those above water since designers try to minimize the forces caused by waves and currents. There is a rule-of-thumb that flow disturbance becomes negligible five diameters behind a cylinder, but this rule is misleading. Under conditions of a strong current and small waves, we have observed vortex streets behind platform legs that extend from one end of the platform to the other.

The integrated effect of many members causes effective blockage, reducing the mean flow both inside and behind the area of the platform. Taylor (1991) described blockage effects of platform members using the concept of an actuator disk. This concept treats the platform as a grid of drag elements and sets the force on the grid equal to the decrease of momentum in a current. For structural members typical of offshore platforms, speeds within the water volume embraced by the outermost members are 75 percent of the undisturbed flow, and speeds in the wake may be reduced by 50 percent.

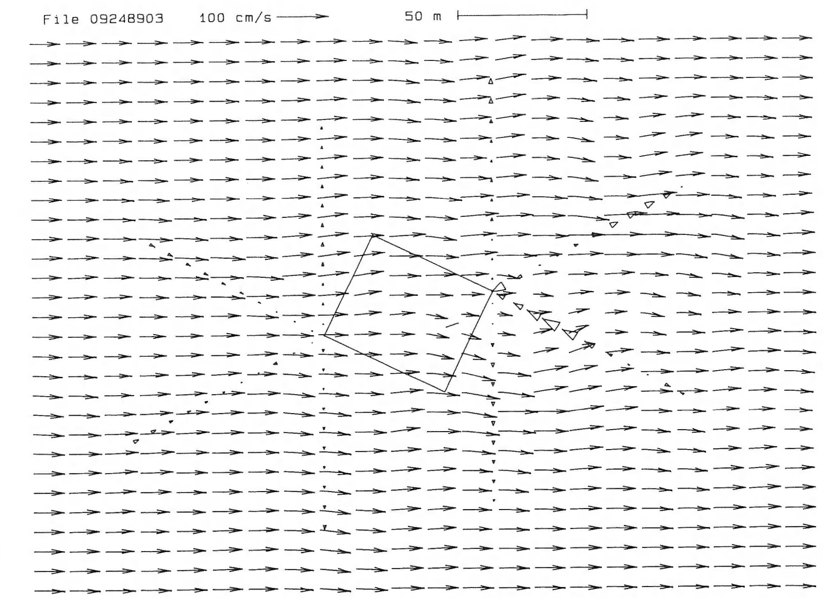
Substantial current blockage has been confirmed both in the laboratory and the field. The total force on a model platform towed in a wave tank was measured by Allender and Petrauskas (1987). They found that the forces of a towed structure were substantially less than expected from the tests in waves alone, an effect possibly explained by blockage. Later, Finnigan (1992) conducted additional tests with the same model, as well as with single- and double-leg platform models. During some tests, a current meter was placed inside the jacket. Both the force and current measurements were consistent with flow blockage.

The Lena guyed platform (a tension-leg type) has many structural members located near the sea surface. Measurements and theory showed that, if member shielding or blockage was not taken into account, forces on this platform in steady currents were overestimated 5- or 6-fold (Steele, 1986; Taylor, 1991).

As discussed in the previous section on major projects, two ADCPs were used to map the flow field in the vicinity of the Bullwinkle platform. Figure 4 shows an analysis of the ADCP currents, during an hour on September 24, 1989, in the presence of strong currents and small waves. In Figure 4, the undisturbed flow, farthest upstream, is from the west at approximately 72 cm/sec, and vectors show the flow field as computed by an objective analysis program that fits the measured velocity components to a stream function. There are large anomalies of velocity inside and downstream of the platform. The current spreads slightly around the platform, and velocity increases at the north and south sides of the platform. The lowest velocity is 58 cm/sec in the middle of the platform, or 0.80 times the undisturbed velocity, and the lowest velocity in the platform's wake is 37 cm/sec, or 0.51 times the undisturbed velocity.

Although the reported results have important implications for calculating forces on platforms, they also show that care must be taken in placing current meters on platforms and interpreting the resulting measurements. For example, the measurements during hurricanes Carmen and Eloise may have been substantially reduced from undisturbed values because the meters were placed at the edges of the platforms (Forristall, 1980). In contrast, the measurements of Forristall et al. (1977) in tropical storm Delia were probably not appreciably contaminated by blockage effects, since the current meters were suspended from the 60 m-long bridge and the currents flowed perpendicular to the bridge.

FIGURE 4. Disturbed current field around the Bullwinkle platform on September 24, 1989. North is at the top of the figure, and the flow is from the west. Scales for velocity and distance are given at the top of the figure.



Difficulties Associated with Platform Motion

Platforms exhibit a wide variety of motions, from high frequencies excited by surface gravity waves to movements of the platform between locations; both types have contaminated previous measurements. The contamination may be subtle, and attention must be given platform motions when calculating statistics from oceanographic sensors. Often the motions of platforms are unimportant for oceanographic measurements, but they must be taken into account for some high frequency sensor systems (e.g., CODAR, MIROS, and OSCR; see Tables 4, 5).

The maximum amplitude displacement of six platform types for typical design conditions is shown in Table 2 (see Figure 1 for platform schematics). Although a platform moves with six degrees of freedom, for brevity only the surge component has been shown in Table 2, where surge is defined as a horizontal motion along the axis of maximum displacement; for most platforms, this is in the direction of dominant waves. Surge depends on water depth; therefore typical water depths in which these platforms were placed are indicated in Table 2.

For most platforms, the maximum surge occurs at the dominant wave period (10-15 sec), though smaller amplitude movements will

TABLE 2. Summary of maximum displacements experienced by six types of platforms.

Platform	Water Depth (m)	Max. Surge (m)
Jacket	100	0.01
Semi-submersible	1000	30
Tension-Leg Platform (TLP)	1000	30
Gravity Based System (GBS)	100	0.01
Caissons	10	1
Drill Ship	1000	30

TABLE 3. Measured parameters and suggested sampling duration of each.

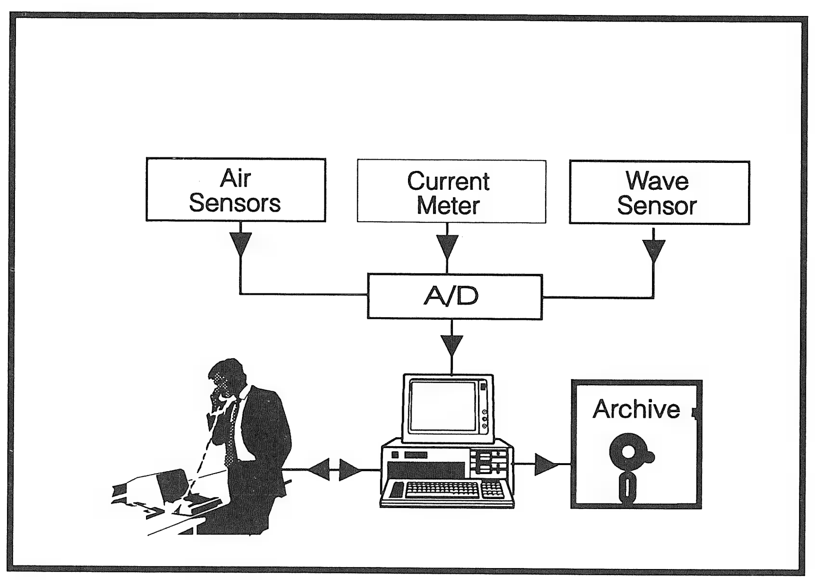
Parameter	Duration[1]
Wind Speed	2 min vector
Wind Direction	2 min vector
Wind Gust[2]	3 sec
Air Temperature	2 min
Air Pressure	2 min
Directional Wave Spectra	17 min
Tide	5 min
Water Temp.	2 min
Current	2 min vector

[1] All parameters, except waves, are averaged over the noted duration. The results are archived hourly to a common magnetic media (e.g., hard disk). The wave sensor is sampled at 0.5 Hz; other sensors at least at 0.1 Hz.
[2] Wind gust is measured by the same sensor as wind speed, but the averaging period differs.

occur at other frequencies and in the other five degrees of freedom. In addition to the platform's forced- and free-mode motions, there may be other motions, including high-frequency machine vibrations, and impact motions caused by docking vessels.

As indicated in Table 2, the motion of stiff platforms (e.g., jackets and gravity-based structures) is sufficiently small that they probably will not affect metocean data. However, motions of more dynamic platforms (e.g., semi-submersibles, TLPs, caissons, and drill ships) will have to be accounted for when making certain measurements (e.g., wind and current measurements must be averaged for several minutes to suppress platform motion).

FIGURE 5. Schematic of the basic components of the generic Metocean Measurement System (MOMS): most frequently used sensors (air, current, wave), analog to digital (A/D) signal conversion, data archival, and a MOMS offshore being assessed from a personal computer located onshore.



A GENERIC SYSTEM FOR METOCEAN MEASUREMENTS

We conclude by presenting a simple, platform-based metocean measurement system (MOMS) that has evolved over the past decade. Schematically represented in Figure 5, data typically are recorded once per hour. Sampling frequencies and averaging durations are shown in Table 3. These settings provide adequate temporal resolution for operations, design, and most research activities in the offshore industry. The cost for a typical MOMS station starts at $40,000, with annual maintenance costs of $10,000. Actual costs are influenced by geographic location and installation costs, particularly the costs of divers.

Tables 4 and 5 provide a summary of commercially available sensors. Further information on sensors may be found in a recent report by the Marine Board (1989).

A standard IBM-compatible PC serves as the "brains" of the system. Real-time access to the PC may be accomplished using telephone lines, standard modems, and remote-access software (e.g., Carbon Copy Plus or PC Anywhere). One of the most important benefits of real-time access is the ability to monitor the MOMS status. Without real-time access, system failures must be identified during routine maintenance or by personnel aboard the platform. While the latter is possible, in practice it is difficult because platform personnel have other fulltime responsibilities and rarely have the necessary training to maintain MOMS.

Atmospheric Sensors

There are many types of anemometer sensors, including cups, propellers, and hot-wires. The R. M. Young model 05103 is perhaps the most frequently used anemometer on oil platforms for the following reasons: wind direction and speed sensors are incorporated into a single device; it can survive high winds (200 kph); it is ruggedly constructed of non-corrosive poly vinyl chloride (PVC); and it has a simple signal interface requiring little active power. The last attribute means that the sensor may be located in places requiring intrinsically safe devices (e.g., derricks).

Measuring atmospheric pressure and temperature is usually less difficult than measuring wind velocity. However, obtaining an ambient air temperature may be difficult because major sources of heat on platforms (e.g., gas flares and compressors) must be avoided. A number of barometric pressure and temperature sensors are readily available; the choice depends on desired accuracy and type of output.

Ocean Sensors

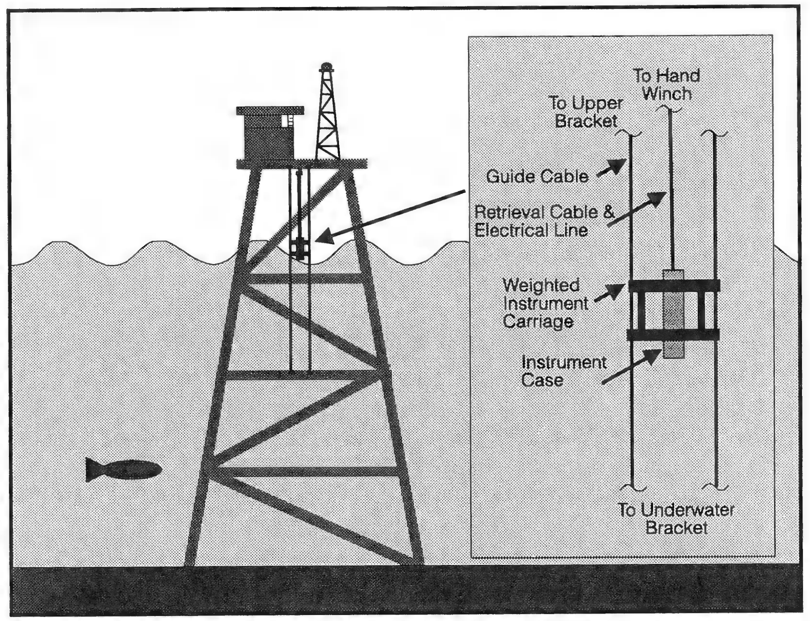
Most of the commercially available sensors used for measuring surface gravity waves are summarized in Table 4. Allender et al. (1989)

TABLE 4. Summary of commercially available wave sensors.

Sensor Type	Strengths	Weaknesses	Example
Wave staff	Moderate cost[1] Measures tide[3]	Installation may require divers[2] Susceptible to lightning[4] Sheltering from platform[5]	Baylor
Subsurface pressure	Inexpensive[1] Measures tide[3]	Installation may require divers[2] Sheltering from platform[5] Attenuated high frequency[6]	Paroscientific
Subsurface travel-time sonar	Inexpensive[1] Measures tide[3]	Installation may require divers[2] Sheltering from platform[5] Affected by density[7]	Datasonics
Above-surface travel-time sonar	Inexpensive[1] Measures tide[3]	Sheltering from platform[5] May include foam in wave height[7] Loss of signal during strong winds[8]	Datasonics
High-frequency radar	No platform sheltering[5] Measures 2-D spectra[9] and surface currents[11]	Expensive[1] Provides statistics only - cannot track individual waves[10]	MIROS
Underwater Doppler Sonar	No platform sheltering[5] Measures 2-D spectra[9] and currents[11]	Expensive[1] Installation may require divers[2] Attenuated high frequency waves[6] Susceptible to fish motion[12]	RDI
Above-surface light	Moderate cost[1] Measures tide[3] Ltd. platform sheltering[5]	May include foam in wave height[7]	EMI, Schwartz
Surface buoy with accelerometer	Moderate cost[1] No platform sheltering[5]	Requires mooring & yearly maintenance Subject to theft and ship collision Very expensive for 2-D[13]	Datawell Waverider

[1] Moderate cost is about $10 k; inexpensive is less than $5 k; expensive is more than $50 k.
[2] Requires at least one underwater mounting bracket. If the sensor is added after the platform is installed, a diver will be required, and this can be costly.
[3] Since this sensor measures sea surface, the signal can be time-averaged to obtain a tide/surge measurement.
[4] May be damaged if lightning strikes in the general vicinity of the platform. All the sensors will be damaged if directly struck by lighting; this is a common disadvantage and not listed separately.
[5] Measures within a few meters of the platform; thus, the measurement may be affected by sheltering of the platform (This issue is discussed in the text.).
[6] Takes a measurement beneath the water surface, so higher frequency waves are attenuated by the water column. This problem can be minimized in most cases by selecting an appropriate sensor depth and sensitivity and doing some additional processing. See Allender et al. (1989) for further discussion.
[7] May give inaccurate readings in the presence of strong density gradients, e.g., subsurface sonar may be affected by a thermocline in water column or air bubbles entrained by breaking waves. Similarly, above - surface light sensors may incorrectly detect foam on the sea surface.
[8] Depending on the beam width and frequency of the sensor, the signal strength may be substantially reduced during strong but not uncommon winds.
[9] Measures directional wave spectra at many different locations on the sea surface, e.g., radar can measure directional wave spectra over a circle of radius 30 km centered at the platform.
[10] Cannot provide a time series of the sea surface; only a statistical measure.
[11] Also measures currents.
[12] May have difficulty discriminating between real water velocity and the velocity from fish.
[13] Buoys are available for measuring directional spectra, but they are very expensive.

FIGURE 6. Schematic of the mounting system for underwater sensors, including current, temperature, and conductivity (right), and jacket platforms (left).



describe extensive tests for some sensors. Under normal conditions, most of the wave sensors require little maintenance.

Tides can usually be measured by averaging the data from the wave sensor over several minutes. Alternatively, a small subsurface pressure transducer can be placed a few meters below the surface, keeping in mind that subsurface measurements must be adjusted for barometric pressure effects.

Wave direction has become an increasingly important parameter for the offshore industry. Many sensors are capable of measuring wave direction either separately or in conjunction with a wave height sensor.

Water temperature and salinity measurements are inexpensive and provide valuable information for oceanographers. Water temperature information is also valuable to platform designers because water temperature can affect many design criteria.

Most of the commercially available current sensors are summarized in Table 5. Underwater sensors typically require periodic cleaning at three-to-six month intervals in mid to low latitudes, depending on the nutrients and type of organisms in the water, and less often in northern latitudes. The cleaning process amounts to carefully removing marine growth from the instruments.

Sensor mounting must be given considerable thought. An underwater sensor may be suspended over the side from a cable with an attached weight, if storms are unlikely. The major advantage of this approach is that it does not require expensive mounts or divers to retrieve or service them.

While fixed sensors are more costly, they will be necessary for long-term studies. Figure 6 shows a schematic of a mounting system allowing retrieval from the sea surface without divers. Although the cost of the mounting system is $2,000 to $3,000, this amount is small when compared with the cost of hiring divers to clean instruments.

TABLE 5. Summary of commercially available current sensors.

Sensor Type	Strengths	Weaknesses	Example
Single point acoustic	Low fouling[1] Moderate cost[3] Solid state	Sheltering from platform[2] Installation may require divers[4]	EG&G
Propeller or Savonious rotor	Low cost[3]	Sheltering from platform[2] Easily fouled[1] Wave rectification[5] Installation may require divers[4]	Aanderaa, ENDECO, EG&G
Electromagnetic	Low fouling[1] Solid state Low cost[3]	Sheltering from platform[2] Susceptible to lightning[6] Installation may require divers[4]	Marsh-McBirney, InterOcean
Acoustic Doppler Profiler (ADCP)	Low fouling[1] Solid state No platform sheltering[2] Profiles water column	High cost[3] Installation may require divers[4] Susceptible to fish motion[7]	RDI
High frequency radar	No fouling[1] Solid state No platform sheltering[2] Extends out to 40 km radius No components in water	High cost[3] Surface current only Radial current only[8]	CODAR, MIROS, OSCR

1 Low fouling means the sensor will function even with moderate marine growth on the sensor, or for at least 3 months between cleanings. Easily fouled means the sensor can be seriously impaired by moderate marine growth and may require frequent cleaning (less than 3 months).
2 Measures within a few meters of the platform; thus the measurement may be affected by sheltering of the platform (This issue is discussed in the text.).
3 Moderate cost is about $15 k; low cost is less than $7 k, high cost is more than $50 k.
4 Requires at least one underwater bracket. If the sensor is added after the platform is installed, a diver will be needed, and this can be costly, i.e., greater than $10-200 k.
5 When installed near the surface, may rectify wave orbital velocities and bias the average vector.
6 May be damaged if lightning strikes in the general vicinity.
7 May have difficulty discriminating between real water velocity and the velocity of fish.
8 Can measure currents only along a radial. To get a 2-D map of currents requires additional radar units at other sites or the assumption that the flow is non-divergent.

Power Considerations

Platform power is subject to interruption and may contain disruptive spikes for sensitive electronics. In locations affected by strong tropical cyclones, it is often standard policy to evacuate personnel and shut down the power on a platform. For these reasons, it is usually advisable to equip the MOMS with an uninterruptible power supply, capable of providing power for several days.

Costs

Table 6 provides a summary of the basic sensors used in a MOMS system. Total cost of installing a MOMS station starts at $40,000 for sites at mid to lower latitudes. Sites at higher latitudes (e.g., North Sea) tend to be stormier; therefore installations are more costly. Total power consumption is about 38 watts.

SUMMARY

Offshore platforms offer a dry, safe, and relatively stable site from which to make met-ocean measurements. Our paper briefly lists some of the larger or more important measurement programs undertaken in the last 40 years. In addition to the important scientific information these programs have provided, they have also demonstrated some limitations to working off a platform. Perhaps the most troublesome one is platform interference. Thanks to lessons learned and recent advances in technology, it is now possible to install an inexpensive, reliable, and powerful metocean monitoring system (MOMS), and some details of such a system have been provided.

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TABLE 6. Summary of specific MOMS configuration.

Device	Manufacturer/Model	Power (watts)	Cost ($ k)
Wave staff	Baylor/23766	1.2	11.0
Electromagnetic Current Meter	Marsh-McBirney/551	1.2	6.0
H_2O Temperature Sensor	YSI/710	0	0.5
Anemometer	R. M. Young/05103	0	0.7
Air Temperature	YSI/705	0	0.5
Barometer	YSI/2014	0	1.0
A/D	Campbell Scientific/CR-10	0.2	1.1
Laptop with 2400 bps modem	Dell 386SX Notebook	12	1.5
Data storage	90 mb Bernoulli	24	0.8
	Total	38.6	23.1

APPENDIX

ACT	AGIP, Chevron, and Texaco group
ADCP	Acoustic Doppler current profiler
ASCII	American Standard Code for Information Interchange
bps	Bits (binary digit) per second
bytes	8-bit grouping of bits
cm/s	Centimeters per second
CODAR	High frequency compact radar system
CRT	Cathode ray tube
CUMEX	Current Measurement Experiment
DATs	Digital audio tapes
gb	Gigabyte (10^9 bytes)
GBS	Gravity based system
FULWACK	Fulmar Wave Crest Kinematics Experiment
GMAQS	Gulf of Mexico Air Quality Study
Hz	One cycle per second
k	Thousand
kb	Kilobytes (10^3 bytes)
mb	Megabyte (10^6 bytes)
METOCEAN	Meteorologic and Oceanographic
MIROS	Microwave Remote Sensor wave/current system by MIROS A/S
MO	Magneto-optical (drives)
MOMS	Meteorological and oceanographic measuring system
MMS	Minerals Management Service
OCMP	Ocean Current Measuring Program

ODGP	Ocean Data Gathering Program
OSCR	Ocean Surface Current Radar current mapping system by Marex
OTS	Ocean Test Structure
PC	Personal computer
PVC	Poly Vinyl Chloride
RAWINSONDE	System for measuring atmospheric wind velocity, pressure, temperature, and humidity in the upper air
RS 232	Receive/send data transmission code
SWAMP	Sea Wave Attenuation Measurement Project
TLP	Tension-leg platform
UPS	Uninterruptible Power Supply
WADIC	Wave Direction Measurement Calibration Project
WORMS	Write-once-read-many (drives)

REFERENCES

Allender, J.H. and Petrauskas, C. 1987. Measured and predicted wave plus current loading on a laboratory-scale, space frame structure (Paper 5371). In: *Proceedings of the 19th Annual Offshore Technology Conference*, pp. 143–151. Houston: Offshore Technology Conference.

Allender, J.H., Audunson, T., Barstow, S.F., Bjerken, S., Krogstad, H., Steinbakke, P., Vartdal, L., Borgman, L. and Graham, C. 1989. The WADIC project: a comprehensive field evaluation of directional wave instrumentation. *Ocean Engr.* 16:505–536.

Battjes, J.A. and van Heteren, J. 1984. Verification of linear theory for particle velocities in wind waves based on field measurements. *Applied Ocean Res.* 6:187–196.

Brown, R.D. and Swail, V.R. 1991. Over-water gust factors. *Ocean Engr.* 18:363–394.

Cardone, V.J., Pierson, W.J. and Ward, E.G. 1976. Hindcasting the directional spectra of hurricane-generated waves. *J. Petroleum Tech.* April 1976:385–394.

Cavaleri, L., Ewing, J.A. and Smith, N.D. 1977. Measurement of the pressure and velocity field below surface waves. In: *Turbulent Fluxes Through the Sea Surface, Wave Dynamics and Prediction*, edited by A. Favre and K. Hasselmann, pp. 257–270. New York: Plenum Press.

Cooper, C.K. and Thompson, J.D. 1989. Hurricane-generated currents on the outer continental shelf, 1, Model formulation and verification. *J. Geophys. Res.* 94:513–539.

Dean, R.G., Lo, J.M. and Johansson, P.L. 1979. Rare wave kinematics vs. design practice. In: *Proceedings of ASCE Civil Engineering in the Oceans IV*, pp. 218–238. San Francisco: American Society of Civil Engineers.

Drennan, W.M., Kahma, K.K. and Donelan, M.A. 1992. The velocity field beneath wind waves—observations and inferences. *Coastal Engineering* 18:111–136.

Earle, M.D., Ebbesmeyer, C.C. and Evans, D.J. 1974. Height-period joint probabilities in Hurricane Camille. *Journal of the Waterways Harbors, and Coastal Engineering Division* 100:257–264.

Earle, M.D. 1975. Extreme wave conditions during Hurricane Camille. *J. Geophys. Res.* 80:377–379.

Ebbesmeyer, C.C., Williams, G.N., Hamilton, R.C., Abbott, C.E., Collipp, B.G. and McFarlane, C.F. 1982. Strong persistent currents observed at depth off the Mississippi River Delta (OTC No. 4322). In: *14th Annual SPE of AIME Offshore Technology Conference*, V. 1, pp. 259–267.

Ebbesmeyer, C.C., Coomes, C.A., Hamilton, R.C., Kurrus, K.A., Sullivan, T.C., Salem, B.L., Romea, R.D. and Bauer, R.J. 1991. New observations on internal waves (solitons) in the South China Sea using an Acoustic Doppler Current Profiler. In: *MTS '91 Proceedings*, pp. 165–175. New Orleans: Marine Technology Society.

Ebbesmeyer, C.C., Coomes, C.A. and Glenn, S.M. 1992. Evolution of Nelson Eddy and the Loop Current during 1989. Final Report. Prepared for Nelson Eddy Analysis Project and Eddy Joint Industry Project.

Finnigan, T.D. 1992. Current blockage effects on model-scale offshore platform. In: *Proceedings of Civil Engineering in the Oceans V*, pp. 294–310. College Station, Texas: American Society of Civil Engineers.

Forristall, G.Z. 1980. A two-layer model for hurricane-driven currents on an irregular grid. *J. Phys. Oceanogr.* 10:1417–1438.

Forristall, G.Z. 1986. Kinematics in the crests of storm waves. In: *Proceedings of the 20th Coastal Engineering Conference*, pp. 208–222. Taipei: American Society of Civil Engineers.

Forristall, G.Z. 1992. Specifying the offshore environment. In: *Proceedings of Civil Engineering in the Oceans V*, pp. 1–41. College Station, Texas: American Society of Civil Engineers.

Forristall, G.Z. and Reece, A.M. 1985. Measurements of wave attenuation due to a soft bottom: The SWAMP experiment. *J. Geophys. Res.* 90:3367–3380.

Forristall, G.Z., Hamilton, R.C. and Cardone, V.J. 1977. Continental shelf currents in Tropical Storm Delia: Observations and theory. *J. Phys. Oceanogr.* 7:532–546.

Forristall, G Z., Ward, E.G., Cardone, V.J. and Borgman, L.E. 1978. The directional spectra and kinematics of surface gravity waves in Tropical Storm Delia. *J. Phys. Oceanogr.* 8:888–909.

Forristall, G.Z., Gutierrez, C.A., Ward, E.G. and Marshall, P.W. 1989. Forces on the Cognac platform in combined storm waves and currents (Paper 6006). In: *Proceedings of the 21st Annual Offshore Technology Conference*, pp. 403–414. Houston: Offshore Technology Conference.

Geminder, R. and Pomonik, G.M. 1979. The Ocean Test Structure Measurement System. In: *Proceedings of ASCE Civil Engineering in the Oceans IV*, pp. 132–148. San Francisco: American Society of Civil Engineers.

Glenn, S.M. and Ebbesmeyer, C.C. 1993. Buoy orbits in a Gulf of Mexico Loop Current Eddy in 1989 (submitted to *J. Geophys. Res.*).

Hamilton, R.C. and Ward, E.G. 1974. Ocean Data Gathering Program-Quality and reduction of data (Paper 2108–A). In: *Proceedings of the 6th Annual Offshore Technology Conference*, pp. 749–769. Houston: Offshore Technology Conference.

Haring, R.C. and Heideman, J.C. 1978. Gulf of Mexico rare wave return periods (Paper 3230). In: *Proceedings of the 10th Annual Offshore Technology Conference*, pp. 1537–1550. Houston: Offshore Technology Conference.

Haring, R.E., Osbourne, A.R. and Spencer, L.P. 1976. Extreme wave parameters based on continental shelf storm wave records. In: *Proceedings of the 15th Coastal Engineering Conference*, pp. 309–319. Honolulu: American Society of Civil Engineers.

Hayes Space Technology. 1986. Current measurements in Block 214/27, West Shetland continental slope, April-Sept. 1985. Report, Feb. 210 pp.

Heideman, J.C. and Weaver, T.O. 1992. Static wave force procedure for platform design. In: *Civil Engineering in the Oceans V*, pp. 496–517. American Society of Civil Engineers.

Lamb, W.C., Hibbard, H.C., James, A.L., Koerner, W.A. and Rothberg, R.H. 1984. Instrumentation for monitoring behavior of the Lena guyed tower (Paper 4684). In: *Proceedings of the 16th Annual Offshore Technology Conference*, Volume 1, pp. 329–338. Houston: Offshore Technology Conference.

Marex. 1980. Environmental conditions in the Forties Field, June 74–May 80. Report 458, Dec. 300 pp.

Marex. 1986a. Environmental conditions in the Brent Field, December 1975–May 1980. Report 732, May. 260 pp.

Marex. 1986b. Oceanographic and meteorological conditions in the Beryl and Frigg fields, January 1979–1982, Report 710–x618, May. 230 pp.

Marine Board, National Research Council. 1989. *Measuring and Understanding Coastal Processes for Engineering Purposes.* National Academy Press, Washington, 119 pp.

Marshall, P.W., Larrabee, R.D., Burk, J.D. and Egan, G.R. 1983. Cognac fatigue experiment (Paper 4522). In: *Proceedings of the 15th Annual Offshore Technology Conference*, pp. 218–228. Houston: Offshore Technology Conference.

Mason, A.B., Ullmann, R.R. and Petrauskas, C. 1992. Platform Hermosa as a wave force transducer (Paper 6813). In: *Proceedings of the 24th Annual Offshore Technology Conference*, pp. 71–78. Houston: Offshore Technology Conference.

Ohmart, R.D. and Gratz, R.L. 1978. A comparison of measured and predicted ocean wave kinematics (Paper 3276). In: *Proceedings of the 10th Annual Offshore Technology Conference*, pp. 1947–1956. Houston: Offshore Technology Conference.

Osborne, A.R. and Burch, T.L. 1980. Internal solitons in the Andaman Sea. *Science* 208:451–460.

Patterson, M.M. 1969. An Ocean Data Gathering Program for the Gulf of Mexico. Presented at the 44th Annual Fall Meeting of the Society of Petroleum Engineers of AIME, SPE 2638, Denver.

Peters, D.J.H., Zimmer, R.A., Hein, N.W. Jr., Wang, W.J., Leverette, S.J. and Bozeman, J.D. 1990. Weight control, performance monitoring, and in situ inspection of the TLWP (Paper 6363). In: *Proceedings of the 22nd Annual Offshore Technology Conference*, pp. 181–194. Houston: Offshore Technology Conference.

Russell, T.L., Schoettle, V. and Chown, R.G. 1966. Ocean wave force instrumentation. J. *Waterways and Harbors Dev.*, 92, WW4.

Sand, S.E., Ottesen Hansen, N.E., Klinting, P., Gudmestad, O.T. and Sterndorff, M.J. 1990. Freak wave kinematics. In: *Water Wave Kinematics*, eds. A. Torum and O.T. Gudmestad, pp. 453–473. Dordrecht: Kluwer.

Seaconsult, Inc. 1985. Hibernia Wave Climate. Report, Sept., 510 pp.

Steele, K.M. 1986. Performance of the Lena guyed tower (Paper 5255). In: *Proceedings of the 18th Annual Offshore Technology Conference*, pp. 289–298. Houston: Offshore Technology Conference.

Swanson, R.C. and Baxter, G.D. 1989. The Bullwinkle platform instrumentation system (Paper 6052). In: *Proceedings of the 21st Annual Offshore Technology Conference*, pp. 93–100. Houston: Offshore Technology Conference.

Taylor, P.H. 1991. Current blockage: Reduced forces on offshore space frame structures (Paper 6519). In: *Proceedings of the 23rd Annual Offshore Technology Conference*, pp. 199–205. Houston: Offshore Technology Conference.

Thornthwaite, C.W., Superior, W.J. and Field, R.T. 1965. Disturbance of airflow around Argus Island tower near Bermuda. *J. Geophys. Res.* 70:6047–6052.

Thrasher, L.W. and Aagaard, P.M. 1969. Measured wave force data on offshore platforms (Paper 1007). In: *Proceedings of the 1st Annual Offshore Technology Conference*, pp. 83–94. Houston: Offshore Technology Conference.

Vyas, Y.K., Lohrmann, A., Heideman, J.C., Dahl, F.E. and Vermersch, J.A. 1988. Storm-driven current profiles for design of offshore platforms. In: *Proceedings of the 1988 BOSS Conference*, pp. 1–16.

Ward, E.G. 1974. Ocean Data Gathering Program: An overview (Paper 2108–B). In: *Proceedings of the 6th Annual Offshore Technology Conference*, pp. 771–780. Houston: Offshore Technology Conference.

Ward, E.G., Borgman, L.E. and Cardone, V.J. 1978. Statistics of hurricane waves in the Gulf of Mexico (Paper 3229). In: *Proceedings of the 10th Annual Offshore Technology Conference*, pp. 1523–1536. Houston: Offshore Technology Conference.

Wills, J.A.B. 1982. Report on the West Sole wind structure project 1982. National Maritime Institute Report R145, 59 pp. London: National Maritime Institute.

PAPER

Long-Range Needs for Deep-Sea Platforms: The Deep-Sea Observatory Concept

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ABSTRACT

The international community of oceanographers and ocean engineers has faced an historical deficiency in long time-series data for all oceanographic and environmental variables in all sea states. Most measurements have been confined to short time-series data collection in the deep ocean during calm to moderate sea conditions by deployment of conventional oceanographic research ships. To a lesser extent, longer time-series have been obtained from moored or drifting autonomous instruments measuring selected (usually physical or optical) variables. A solution to this deficiency is to deploy a complete oceanographic deep-sea observatory designed into a large mobile ocean platform with small water-plane area displacement. This deep-sea observatory would be maintained at sea for periods in excess of five years with logistics and scientific resupply accomplished through the technologies developed during the last decade by the offshore ocean industry. Platforms of this design would provide fundamental information about the structure and dynamics of open-ocean ecosystems far from land and would enable greatly improved ground-truth information about the state of the ocean environment.

INTRODUCTION

The idea of a deep ocean research observatory based on a large stable platform is not a new one. The Stratton Commission noted that

> An example of a project which the commission believes merits further feasibility study is the large stable ocean platform. The utilization of semi-submersible drilling platforms by the petroleum industry has proved that, when further developed, such platforms can provide highly flexible, multipurpose, all-weather islands capable of remaining on station in the open ocean for long periods. The size, stability, and long-endurance station keeping capabilities of these platforms will permit them to be used in support of air and sea transportation, resource development, environmental monitoring, and military missions (Stratton Commission, 1969, page 38).

A workshop at the Woods Hole Oceanographic Institution in 1985 studied the possible use of the ocean drilling ship *JOIDES Resolution* for ancillary multidisciplinary time series. The value of the time-series approach was obvious, but the drill-ship, because of space limitations and too frequent relocations, turned out not to be a viable platform. One result of this workshop was a short note (Wiebe et al., 1987) that discussed the scientific rationale for multidisciplinary time series, gave some examples of the new insights afforded by the few and fragmentary time series that did exist, and offered an initial assessment of platform options, site considerations, and core time-series specifications.

During the same period, in a separate effort, the Marine Physical Laboratory of the Scripps Institution of Oceanography obtained funding to study possible new platforms to replace the aging manned spar buoy FLIP. Among the platforms for which a body of engineering and economic information was obtained was a typical self-propelled semi-submersible rig, the Western Pacesetter III, which was at that time under the ownership of the U.S. Maritime Administration (MARAD). Several reports on this platform's capabilities and the costs of refitting it for science were developed by the Scripps Institution of Oceanography. The possibility of obtaining the Western Pacesetter III, a federal asset, for scientific use as a deep-sea observatory was discussed in a number of public forums, and seriously considered, but subsequently abandoned.

In 1989, the prospect of establishing a deep-sea observatory took a radical new tack, driven by wholly nonscientific concerns. The U.S. Congress mandated that the military perform an active role in the Nation's war against illegal drugs. On September 5, 1989, President George Bush announced a broad agenda for illegal-drug control which included a Gulf of Mexico at-sea radar barrier.

At high levels within the Department of Defense (DoD), it was decided that one part of the military contribution might be for the U.S. Navy to acquire and modify two semi-submersible platforms, specifically the Western Pacesetters II and III, and to deploy them in the central Gulf of Mexico. Both platforms would operate high-altitude (4,600 m) balloon-borne radars that would complete a picket fence of such radars along the whole southern border of the United States. This campaign created a third potential supporting function for a deep-sea observatory as part of the counter-narcotics surveillance system in the Gulf of Mexico or Caribbean. The combination of these missions was presented as a cooperative endeavor to address timely solutions to military, scientific, and social issues in the marine environment. Unfortunately, shortly before implementation of the work to refit the platforms, this program was also abandoned.

Planning, however, directed toward the investigation of an oceanographic laboratory at sea was realized through a joint government/university/industry workshop known as the Deep-Sea Observatory (DSO) Workshop (DSO Organizing Committee, 1990). This workshop was sponsored by the David Taylor Research Center, the Scripps Institution of Oceanography, and the Woods Hole Oceanographic Institution in November 1989. The workshop had two broad purposes. The first was to continue scientific assessment of the deep-sea observatory concept in general terms, not tied to any specific platforms; to refine ideas about science that could be done better, or only, from a deep-sea observatory; and to identify individual scientists interested in working on the ongoing development of this concept. The second objective was to discuss the Gulf of Mexico platforms, both their capabilities and operational constraints; to assess the near-term opportunities for science on these platforms; to frame recommendations for the Department of Defense on how to maximize those opportunities both in the physical refit of ocean oil exploration platforms and in their operational methods; and to identify individual scientists interested in carrying out research on these platforms.

The report of that workshop (DSO Organizing Committee, 1990) concluded that the combined scientific, military, and surveillance potential of a converted semi-submersible platform was undisputable. This conclusion echoed a similar report on the military potential of semi-submersible platforms by Ramsey (1989). He said, "The feasibility of a long-term marriage between selective military and commercial offshore industry technologies is long overdue and now appears to present attractive opportunities that could be explored in partnership with academia. It seems timely for renewed consideration of marine technology concepts having dual benefit and for a dedicated study of technology transfer options that can, and should be exploited to their fullest. . . . "

In a significant development, the National Science Foundation initiated the Ocean Enterprise Concept in 1989 with the overall objective of providing a viable solution to the common perception of high risk in ocean developments.

> The basic problem in ocean development is that new uses of the ocean are perceived as having overly high risks and diminished government support and interest. The Ocean Enterprise Concept was formulated as a way of overcoming the constraints that have inhibited the development of Exclusive Economic Zone (EEZ 1983 200 nautical mile Presidential Proclamation) resources and uses. By allying government, industry, and academia, the gap that exists between research and development in ocean projects could be bridged with private/public funding to support special development activities.
>
> The lack of a U.S. national infrastructure has inhibited the development of ocean enterprises. To develop ocean enterprises, funding for large-scale ocean projects is needed outside of the nation's current operating budgets in order to keep from sacrificing other national political, social, and economic goals. These enterprises (e.g., large floating platforms, etc.) should be funded out of capital accounts and then reimbursed on a fiscally sound basis when the private or public users benefit (Ross and Dailey, 1989).

The Ocean Enterprise Concept is sound but is somewhat limited by an emphasis on a purely national investment in an international resource. The concept of ownership in the great ocean basins must be separated from the concept of exploitation. The technical basis for this separation resides in the skill with which our oceanographers can understand the processes of the seas, and this in turn rests upon their ability to live and work in the ocean environment.

SYNOPTIC VISION

The deep-sea observatory is proposed as a cooperative endeavor to supply the Nation simultaneously with an at-sea research capability for naval and ocean systems and to serve the oceanographic industry as a national resource for research. The concept involves the development of a large (25 kilotonne) semi-submersible or small water-plane area platform similar to or converted from existing offshore oil exploration and drilling platforms (see inside back cover of this issue). The deep-sea observatory is designed as a mobile seagoing research facility able to stay at sea for periods exceeding five years.

The navy's oceanographic research has historically been conducted from ocean-going research ships of modest size and conventional design. Further, ". . . prior to 1960, the oceanographer in his ships, with few exceptions, had to content himself with miscellaneous jury-rigged conversions." (Behrens foreword in Neison, 1971). These ships have served the needs of the navy well for the accumulation of oceanographic data except for their inherent limitations in the collection of long time-series. The immense progress we have made in this past decade to explore and exploit our planet's water resources has in large measure been made possible by the specially designed oceanographic ships that have been built."(Behrens, ibid). These ships are data collectors and research vessels which use the marine environment as a research site for oceanographic and other critical technological work. ". . . we are caught in a paradoxical web . . . the more we learn and the farther we venture, the greater the demands we must place upon our facilities. Our new tools of yesterday thus become tomorrow's obsolescent ships." (Behrens, ibid).

This "paradoxical web" is actually a major challenge to scientists, ocean architects, and naval architects. We must create the special tools necessary for us to achieve a heightened understanding of our ocean environment and to provide for the appropriate and environmentally safe exploitation of our ocean resources. This challenge has led us to realize the need for a new paradigm in ocean observation platforms. No longer can we be scientifically content with the sporadic and disconnected point measurements in space and time in the ocean. We must redirect ourselves toward an understanding of oceanic phenomena based upon a full appreciation of the temporal and spatial variables, which requires that observations be made at many places continuously for long periods.

The oceanographer will come and go from his laboratory in the ocean, but the deep-sea observatory and its measurement capabilities must stay in place and await his or her return. The laboratory must remain at sea and it must be a part of the environment.

THE OCEANOGRAPHIC REQUIREMENT

For some time a number of scientists have realized that the best way to make a quantum step forward in our understanding of how open-ocean ecosystems function and are regulated is to gather many long, frequently-sampled, simultaneous time-series of the important variable quantities in those ecosystems and to study them as time series for inter-correlations or cross-spectra. A good deal of consideration has already been given to the kinds of oceanographic research programs that might be established on such a laboratory at sea. With regard to the core time-series, a proposed list of critical variables and sampling rates has been published (Table 1). The important variables include physical ones, such as salinity, temperature, and current; chemical variables, such as dissolved nutrients; and biological parameters, such as primary production and macro-zooplankton abundance. They include a range of meteorological and air-sea interaction parameters that govern the surface forcing of the ocean and the field of incoming radiation. Some modifications to this table may now be needed (e.g., it now is possible to use acoustic profiling of currents to much greater depths than 200 meters). Sampling must be of long duration because there is much obvious and energetic seasonal, annual, and interannual variability in any open ocean location, and sampling must be frequent to resolve the effects of brief but energetic perturbations (e.g., storms).

A solution to these related needs of the oceanographic community lies in the creation and operation of a deep-sea observatory specifically designed to be capable of sustaining long time-series of core measurements (see inside back cover of this issue). An oceanic observatory must be a manned facility, because a significant number of the crucial measurements cannot be done except in laboratories by people. It must be able to operate continuously for long periods of time and in all weather conditions. These constraints point toward a large, stable platform. A semi-submersible drilling rig of the kind used in offshore oil exploration is an attractive candidate for the scientific mission. Large platforms will allow operations to continue at moderately high winds (40 to 50 knots, or 20 to 25 m/s) and sea states. Thus, the importance of energetic events in setting the oceanographic mean condition can be evaluated.

TABLE 1. Proposed list of core time-series measurements (taken from Wiebe et al., 1987).

High Frequency Suites
(Daily or continuous in some cases)

Physics (atmosphere)
- Outgoing long-wave radiation
- Wind speed and direction
- Relative humidity
- Barometric pressure
- Surface air temperature
- Light 0.3 to 3 μm

Physics (ocean)
- Wave conditions
- Sea surface temperature
- Conductivity, temperature, depth (0-1,000 m)
- Currents (0-200 m; acoustic profiling of ocean currents, or APOC)
- Currents (greater than 200 m; moorings)
- Submarine light to less than 0.1% of surface illumination

Chemistry
- Dissolved nutrients (NO_3, NO_2, NH_4,UREA, SIO_4, PO4: 0-500 m)
- Total CO_2, alkalinity, pCO_2
- O_2

Biology
- Microbial carbon (in euphotic zone)
- Phytoplankton carbon (in euphotic zone)
- Chlorophyll profile (plus phaeopigments)
- Microzooplankton carbon (euphotic zone plus integrated 0-1,000 m)
- Macrozooplankton carbon (euphotic zone plus integrated 0-1,000 m)
- Micronekton by acoustics
- Size frequency distributions of living matter (euphotic zone)
- Primary production (to 0.1% light)

Lower Frequency Suites
(Weekly or so)

Physics (ocean)
- Lagrangian currents (drifters)
- Deep conductivity-temperature-depth (CTD) casts (0-2,000 m)
- Deep currents (moorings)

Chemistry
- Argon, ^{3}He, particulate organic carbon (POC), nitrogen (PON), phosphorous (POP), and silicon (PSI), (0-2,000 m)
- Dissolved organic carbon (DOC), nitrogen (DON), and phosphorous (DOP)
- Dissolved nutrients (0-2,000 m)
- Deep total CO_2, alkalinity, pCO_2
- Sinking particles (traps, upper 2,000 m)

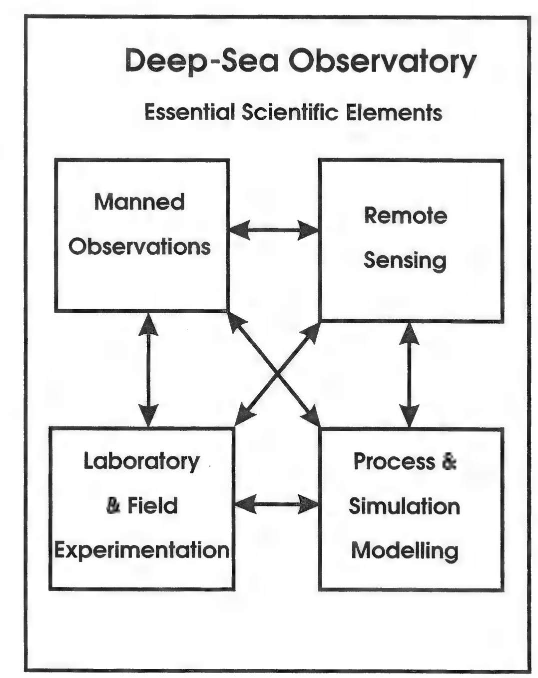
Biology
- Depth stratified sampling for all size categories (day/night to 1,000 m)
- Replicate water column primary production (three to four per depth per day biweekly)

A platform large enough to have these operating capabilities is able to support considerably more research effort than just the collection of core time-series. The need is to provide for all of the scientific elements now recognized as essential to a balanced and comprehensive research program (Figure 1). There should be ample facilities and opportunities for complementary laboratory and field experimental studies. This approach involves studies of the fluxes of energy or materials between different biological categories rather than studies of the time variation of the aggregated categories themselves, as emphasized in the time-series approach. It is clear that the interpretation of such flux or rate results can be enormously enhanced when these observations are made in parallel with the time-series observations, for the latter affords the essential context of natural variability where the rates are not independent of the states or sizes of the aggregated categories. The combination of such rate studies and time-series studies on the DSO coupled with a variety of satellite and other remote sensing instrument data and appropriate modelling (Figure 1) will clearly lead to results of greater value than the sum of separate efforts.

Many such studies in both biology and chemistry require a constant supply of large volumes of fresh oceanic seawater (not coastal or estuarine) from a variety of depths. Investigations of control mechanisms regulating the flux of carbon between its organic and inorganic phases, the cycling of nutrients, and the allocation of primary production require in situ measurements in oceanic systems because the milieu in which these processes occur simply cannot be imitated in laboratories. Studies of this kind would be ideally suited to a large, stable, deep-sea observatory. Such uses for the DSO would be similar in kind to the relatively short-term investigations carried out at astronomical observatories. Their scientific interpretations would be enhanced in a similar way by being done in the context of the ongoing long-term studies. The DSO also offers unique opportunities to operate complex or delicate instruments that are taken to sea on conventional ships only rarely, or briefly, and thus are never able to sample the ocean under the full range of natural conditions. Lack of measurements in severe storms is particularly acute; research vessels are incapable of doing serious work in them. Many measurements of the evolution of the upper ocean and lower atmosphere can be made from an offshore platform under storm conditions. Research radars and lidars for sampling the marine atmosphere can be deployed and operated routinely from aerostats (Figure 2) along with other essential atmospheric and oceanographic measurement instruments. Space constraints, structure interferences, and ship motions make this next to impossible on conventional vessels. Detailed profiling of the temperature, salinity, and current can be done as frequently as desired, to full ocean depth, and can proceed through the worst weather.

There seems to be little question now that long-term monitoring of the earth's major environmental systems will be an absolute requirement in the near future, if not now. Because of their immense size, the open oceans play a major role in global geochemical cycles. Deep water and sediments serve as reservoirs or

FIGURE 1. A schematic drawing of the essential scientific elements required to enable a comprehensive program of open ocean and atmospheric research. Manned observations and remote sensing data constitute the observational element. Laboratory and field experimental manipulations of organisms constitute the experimental element. Process and simulation modelling based on first principal formulations or from existing data constitute the third element.

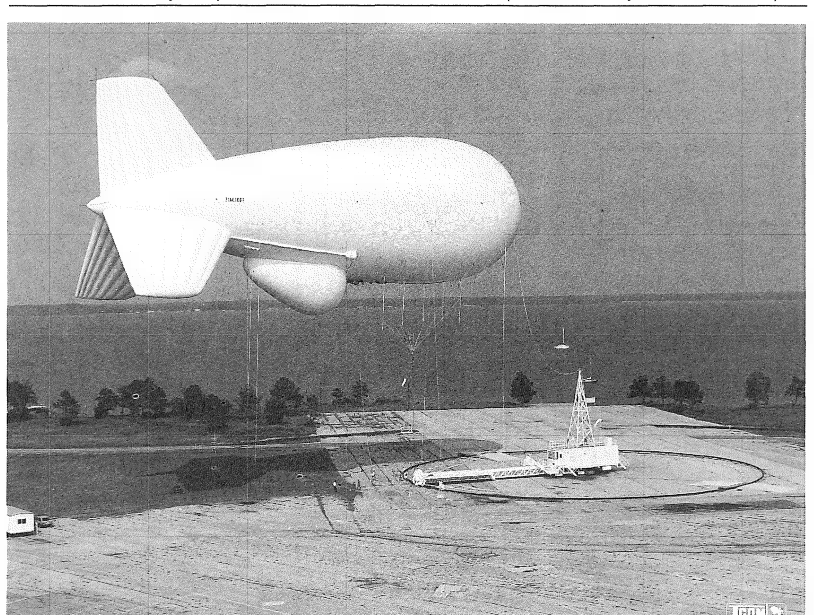


sinks that sequester both natural and anthropogenic materials. The CO_2 increase in the atmosphere is predicted to cause a greenhouse effect which in tum will heat the earth. The magnitude and distributions of this heating and its likely effects on rainfall, agriculture, sea level, and coastal habitation are all very uncertain at present and cannot be confidently predicted. The range of possible consequences, resulting from the best models is very wide. A large part of this uncertainty is due to a lack of adequate data on oceanic conditions and perhaps a lack of understanding of oceanic mechanisms. Monitoring an array of variables in the open ocean under the full range of natural conditions is indispensable to narrowing the uncertainty of model results in the future.

As indicated above, a substantial number of the programs, core and other, will need repeated access to the water column from the platform in order to lower instruments and recover samples. An array of winches, handling gear, sampling instruments, pumps with intakes at various depths, and other equipment will be required. The great size of the DSO makes it feasible to spread these pieces of gear out, so they do not interfere with each other on deck Interference of wires in the water is another matter; there will be a need for scheduling the various lowerings, and a competition between projects for "wire time," much as there is now on conventional vessels.

Laboratories on the platform will be remarkably like their shore-based counterparts.

FIGURE 2. The TCOM aerostat is a helium-filled aerodynamically shaped balloon that is 71 m long and 18 m in diameter. It can remain on station for up to 30 days and can fly up to 4,500 m. Instruments are enclosed in a streamlined air-filled compartment windscreen beneath the aerostat, where they are protected from wind and weather. (Photo courtesy of Ira Sussman.)



The sheer size of the platform means that some of the acute pressures that arise on a normal ship-for example, cramped laboratory space and lack of stability in a seaway-will be greatly decreased. First-class laboratory spaces can be built in for the more or less permanent operations and brought on and off the platform in conventional shipping containers for more transient operations. With high-speed satellite communications much information can be transferred in both directions in near-real time.

The platform's capability to act as a central base for a variety of instruments and measurement programs in the local region opens up the possibility of sustaining regional observations of some key variables by sampling from a platform-based work-boat or from various drifting and moored autonomous instruments. The ability to launch and recover autonomous underwater vehicles (AUVs) under virtually all weather conditions would enable the ocean environment to be studied in ways not possible today. Platform size permits a rather large and capable vessel to be housed aboard the platform so that extensive arrays of instruments and extensive boat-based sampling routines can be sustained away from the platform itself. Regional extension of the DSO is easiest to achieve in the measurement of physical variables. While some of the more complex biological measurements (Table I) must be confined to the platform and to samplers operated directly from it (Figure 3), many physical measurements are readily extended into the surrounding region (see inside back cover of this issue). A modest platform-based boat can make temperature measurements, launch drifting buoys, and tend nearby moorings. Doppler sonars can sample currents over ranges of kilometers. All of these observational techniques, coupled with dynamical models of mesoscale ocean circulation, make it eminently feasible to obtain an excellent ongoing picture of the regional physical oceanography; this will be extraordinarily powerful information with which to separate space and time variability.

In the field of wave/wind climatology, the DSO will provide real-time measurement of ocean wave height, period, and direction that are essential for accurate assessments of full-scale ship seakeeping performance. The platform can be used as an environmental monitoring station to measure additional factors significant to ship performance such as wind and current speed and direction. Successful use of the platform in this role will depend upon location of the platform, size of the platform, and accessibility.

The availability of the research capabilities of the DSO creates a potential for solving a significant number of technical problems both inside and outside the purview of traditional oceanography. The capabilities also address technical issues not previously thought possible.

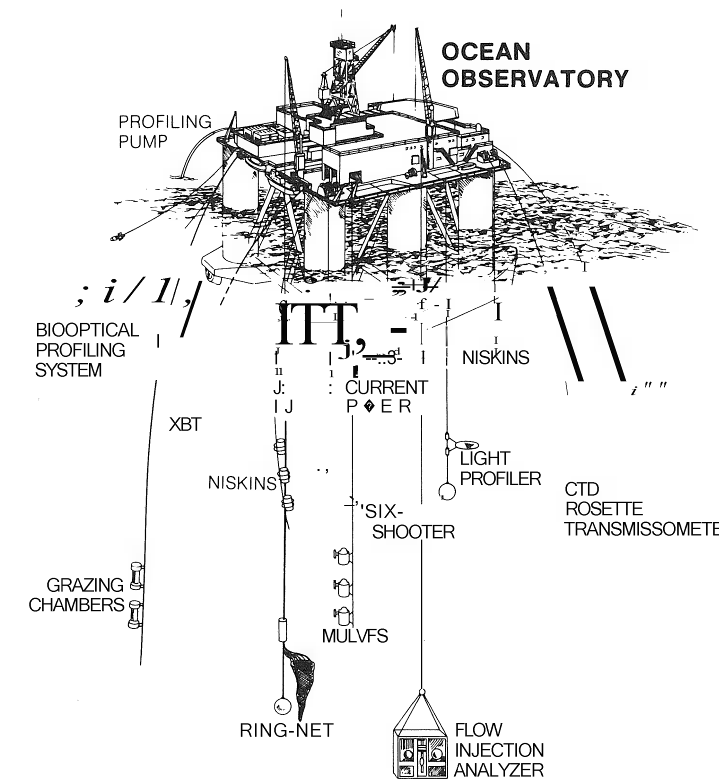
DEFENSE RESEARCH APPLICATIONS

The opportunity for the development of a defense systems research laboratory located in deep water has also recently emerged from the offshore oil exploration industry. The concept proposed is similar to the DSO in that it involves the conversion of an existing offshore oil exploration and drilling platform into a large semi-submersible self-contained deep-ocean research observatory (Moran and Metrey, 1991). The military potential of semi-submersible platforms was recently discussed by Ramsey (1989). He said that "military experiences make apparent that commercial marine technologies and the selective use of offshore oil industry platforms are already playing an important support role in naval operations" from the British experience in the Falkland Islands campaign to the rescue of the *USS S.B. Roberts* in the Persian Gulf. The review goes on to address sustained all-weather global operations, such as repair bases for damaged ships, forward deployed mobile operating bases, command platforms, and mother-ship control platforms.

Consideration of defense systems research and development greatly extends the range of applicability of semi-submersible platforms. "The semi-submersible's low radiated-noise signature, superior compartmentalization, and seakeeping, precise maneuvering and station keeping are but a few of the advanced marine technology features worthy of military consideration" (Ramsey, 1989). While many technological issues could be uniquely served by an at-sea research and development laboratory, a number of defense system research areas have received serious attention:

- An offshore platform-based ship signature facility would provide radar signature characterization of the navy's operational fleet. This facility would be superior to a shore-based site. Both options would employ aerostat (Figure 2) elevated stabilized radar transceivers in a broad frequency range. The platform has the advantages of better sea conditions, increased lookdown angle, greater operational time, and cost effectiveness.
- As an autonomous underwater vehicle (AUV) facility the platform would replace current ad hoc ship-based research platforms which are normally leased and configured for specific tests. The dedicated site would allow a fuller promotion of AUV research and development capabilities and lead to a more rapid application of AUV technology in the navy. The platform has the advantages of open-ocean accessibility and permanency of technical resources, auxiliary ships, and tracking ranges.

FIGURE 3. Illustration of some of a wide array of physical, chemical, and biological instruments that would be deployed from the deep-sea observatory.



- Current research in anti-submarine warfare involves the concept of surveillance platforms towing long sonar arrays. It is anticipated that this system might be supported by a large "mother-ship" submersible or semi-submersible.
- For navy materials corrosion research, the navy currently maintains several shore-based corrosion laboratories. An ocean platform has the advantage of open-ocean seawater circulation and appropriate environmental conditions. Areas of interest include topics such as in situ studies of hull fouling and hull roughness. Plates suspended from the DSO may be used to grow various degrees of fouling or roughness. The same plates may then be tested in model towing tanks to quantify resistance values. This information is necessary to quantify the economic benefits of anti-fouling coatings. The capability also exists for long-term at-sea corrosion tests on tow-cables and towed components. The number of tests and monies saved in a platform-based site would be significant since the cost of developing the laboratory is roughly equivalent

to the development of an improved shore-based site.

- As a future materials reflectivity (radar) facility, the use of the platform for research and development related to the radar absorbency and reflectivity of materials and coatings in a marine environment covers three program areas: (1) the basic analysis of radar reflectivity in an open environment subjected to seawater; (2) simultaneous angle dependence for low angle radar reflectivity studies in the presence of a disturbed ocean surface; and (3) at-sea materials, radar reflectivity tests on ship structure configurational coatings. These all benefit from a stable low-cost alternative to aircraft-borne radar facilities.
- Acoustic materials have an inherent depth dependence on acoustic absorbency. Materials for submarine coating require evaluation to the full pressure depth expected in application. All of the depths required are not reachable in currently available facilities. The platform would also provide the opportunity for depth acoustic testing in unconfined space. Modification of the platform to provide a deep ocean target strength facility is straightforward and inexpensive.
- The DSO provides ready access to one of the natural characteristics of the ocean, i.e., great in situ pressures. Testing of hydrostatic and dynamic structural capabilities of any underwater vehicle or structure can be performed simply by lowering the test body to the desired pressure depth. Structural testing for shock survivability is similarly obtained safely in the ocean depths.
- The navy has recently expressed a desire to explore the use of semi-submersible platforms as alternative offshore bases in areas where better or friendlier capabilities are needed. Using existing platform technology would provide initial analysis of semi-submersible applicability to offshore basing at minimal cost to the government.

The proposed platform must meet a number of critical requirements in order to satisfy any of these applications. The most obvious requirement is for self-sustained operation and station-keeping at sea under all of the most extreme wave and weather conditions. The station-keeping capability of most platforms normally exceeds the tolerances required for the defense systems' research missions. The platform must also have sustained personnel support and habitability capabilities. Again, most existing platforms exceed these requirements. Heavy lift equipment is essential to the military research missions and, fortunately, the existing drilling equipment is normally designed for extremely large loads relative to research requirements. Another key element to success of the DSO is the availability of large deck area and large volume of laboratory space below decks.

DESIGN CHARACTERISTICS

In our view, the conceptual sea-based deep-sea observatory is a twin-hull semi-submersible ship with a nominal working condition displacement of 25 kilotonnes and a transit displacement of 14 kilotonnes. The ship has a hull length of approximately 79 m with an overall beam of 67 m. It is built upon hulls each 15 m in beam and 6 m deep. The water-plane area is developed by six circular-shaped caissons, each 10 m in diameter. The ship is dynamically designed to have natural pitch and roll periods equal at approximately 35 seconds and a natural heave period of some 20 seconds.

The overall height of the DSO from keel to helicopter landing deck is some 39.6 m. The ship is designed to transit at speed on her lower hulls drawing less than 6 m. At a stabilized operating condition the ship will have an operating draft of 18.3 m. The superstructure consists of three working decks covered by an upper deck 61 m long and 61 m wide. The prime movers are multiple sets of matched 2,000 HP diesel engines and 1,500 KW AC generators. Propulsion motors are rectified DC electric motors driving conventional and tractor propulsors. All maneuvering power is provided through differential thrust of the propulsors.

The lower three decks are open to the sea through a well 15 m square through the center of the ship. The deck above the well supports both the heavy and light lifting gear so that all ocean cables can be operated within the confines of the ship spaces if necessary. Over the side operations are permitted through the use of two 36.5 m motion stabilized cranes that are located so that they provide access to the deck loading spaces. Loading of containers and laboratory container spaces can be accomplished either over the side or through the center well ("moon pool") of the ship. In general the ship is designed to provide full access to the center well and the associated heavy-lift gantry crane, including provision to attach and detach heavy packages on wires. It is also important to provide the center well with a working platform that can be lowered to the water surface.

Main machinery air cooling discharge vents must be located so as not to interfere with atmospheric measurements and the ship must provide advanced sewage treatment with holding tanks to minimize platform pollution of the local environment. Air-locked sea chests and external hull-mounted precisely-surveyed transducer attachments will be provided for scientific transducers in both hulls. Separate noise and vibration-isolated generators for quiet ship operations will also be provided with capacity to meet all shipboard needs.

The ship will provide space and utilities for portable vans, including pumped seawater. In addition to the containerized laboratory modules, the configuration will provide fixed interior laboratory spaces, some with precise temperature and humidity control for delicate chemical and biological analyses. In all cases the design will assure a laboratory electrical power supply not subject to fluctuations due to ship machinery operation. Biological studies will require an uncontaminated surface seawater supply to laboratories and to continuous sea surface temperature and salinity sensors. This will necessitate provisions for a scientific pumping system to draw approximately 4 m^3 per minute of seawater through large diameter plastic pipe deployable to variable depths up to 300 m.

The ship will incorporate two I-beams beneath the flight deck for loading capabilities and experimental packages. Each should project to its edge in the forward and starboard directions and should be capable of supporting a traveling block carrying a 4,545 kg load. The ship will also need all of the support requirements for an oceanographic winch with electro-mechanical cable to carry out full-depth conductivity, temperature, depth casts and associated water sampling. For deployment of instrumentation close to the ship, the design will also provide two 61 m swinging booms at opposite corners of the vessel for meteorological and oceanographic instruments.

PLATFORM HABITABILITY

Scientists and technical staff generally expect cramped quarters and limited entertainment while working at sea. Currently, most individuals do not go out to sea very frequently or for very long intervals (usually six weeks is about maximum). However, a laboratory designed to remain at sea for years and to support staff through many work cycles *must* be comfortable and enjoyable. A high standard of material comfort on DSOs will be a good investment in terms of productivity, stress level, and retainment of experienced staff. The following suggestions for amenable conditions are culminated from considerable experience on ships of different sizes:

- single or double staterooms with adjoining bath;
- staterooms equipped with entertainment video, computer, and telephone terminals;
- spacious consolidated messing facility with consistently high quality food and snack bar;
- two lounges—one lounge for entertainment and another for service as a library or conference room;
- an exercise room with modern exercise machines and sauna;
- laboratories designed to be vibration and noise free and which should be scientifically functional and based on design inputs from practicing scientists.

CONCLUSION

The deep-sea observatory is a necessary asset to our continued international search for understanding of the oceans. The continued exploration of the seas and the great ocean basins is essential to the thoughtful exploitation of the resources upon which the human population will increasingly depend in the future.

ACKNOWLEDGMENT

This paper was a direct development of the efforts of the 1989 DTRC Workshop Participants who energetically endorsed the DSO concept and provided valuable assistance in developing the basic information for the 1990 report. We especially wish to acknowledge the guidance and collaboration we have received over a number of years from Dr. Roy Gaul. This work was supported by private grants from the Woods Hole Oceanographic Institution and the Scripps Institution of Oceanography. This is contribution number (8335) of the Woods Hole Oceanographic Institution.

REFERENCES

*DSO Organizing Committee. 1990. Deep-Sea Observatories: Near-Term Opportunities and Long-Range Goals. Report of a workshop held at the David Taylor Research Center, Bethesda, MD, November 7– 9, 1989. *(R. Knox, J. McGowan, P. Wiebe, C. Miller, D. Caldwell). 54 pp.

Moran, D.D. and Metrey, R.E. 1991. The deep ocean research observatory—A naval laboratory at sea. In: *PACON-90 Proceedings.* Honolulu, HI: The Pacific Congress on Marine Science and Technology.

Nelson, S.B. 1971. Oceanographic Ships: Fore and Aft. U.S. Navy Document 0842– 0050, 240 pps.

Ramsey, R. 1989. The military potential of semi-submersible platforms. *Sea Technology.* 30 (2): 57– 58

Ross, D.A. and Dailey, J.E. 1989. The Ocean Enterprise Concept, Report on the Ocean Enterprise Workshop. National Science Foundation, ENG 8806461.

Stratton Commission. 1969. Our Nation and the Sea. A plan for national action. Report of the Commission on Marine Science, Engineering and Resources. Superintendent of Documents, U.S. Government Printing Office. Washington, D.C. 305 pps.

Wiebe, P.H., Miller, C.B., McGowan, J.A. and Knox, R.A. 1987. Long time series study of oceanic ecosystems. *Eos,* 68(44): 1178– 1190.

PAPER

Automated Instrumentation for Time-Series Measurement of Primary Production and Nutrient Status in Production Platform-Accessible Environments

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ABSTRACT

A major limitation to the assessment of the temporal and spatial variability of key ecological parameters is the ability to perform complex biological and chemical procedures autonomously in situ. We present new instrumentation for the automated in situ measurement of photosynthesis and other microbial processes and for assessment of micro-nutrient pools in coastal and oceanic environments. High resolution time-series studies of photosynthesis using a submersible incubation device (SID) indicates that the standard sampling interval commonly employed in coastal and oceanic studies can lead to significant errors in the determination of the temporal patterns of photosynthesis and quantification of integrated measures of production expressed on a seasonal or annual basis. Clearly, methodologies that allow for the higher frequency measurements required to quantify this key ecological parameter adequately are needed. In addition, SID technology was found to avoid both potential handling artifacts of standard techniques. Since photosynthesis rates must often be interpreted in context with the nutrient regime of the environment, an autonomous in situ continuous flow chemical analyzer (in situ-CFA) has been developed for parallel deployment with the SID. Both SID and in situ-CFA instruments, when incorporated into regional arrays of automated moorings that are supported by offshore platform research programs, should greatly facilitate the gathering of data essential to our understanding of the meso-scale processes controlling biological systems in the coastal and oceanic environment.

INTRODUCTION

Quantitative understanding of nutrient status and primary production are crucial measures for investigating the ecology and/or biogeochemistry of aquatic ecosystems. Phytoplankton are in contact with their environment at a physiological level and are, hence, strongly coupled to water column temperature, light field, and nutrient chemistry. The potential for large amplitude and high frequency fluctuations in physiologically important chemical and physical variables, coupled with effects of zooplankton grazing and passive transport by water column circulation, all combine to strongly influence primary production in time and space (Dickey, 1990; 1991). Natural variability in lacustrine (e.g., Cole et al., 1989), coastal (e.g., Lewis and Platt, 1982; Nixon et al., 1986; Lohrenz et al., 1987; Dustan and Pickney, 1989; Mills and Tett, 1990; Sanford et al., 1990; Taylor and Howes, *ms. subm.*), shelf (e.g., O'Reilly and Busch, 1984; O'Reilly et al., 1987; Walsh et al., 1987; Horne et al., 1989; Bisagni, 1992), and oceanic (Dickey et al., 1991; Falkowski et al., 1991; Lohrenz et al., 1992; Michaels et al., *in press*) environments can be surprisingly high, and events of major ecological significance may result from sporadic perturbations (e.g., Jenkens and Goldman, 1985; Dickey, 1990; Dickey et al., 1991; Marra et al., 1990). Present strategies must emphasize approaches that substantially increase the temporal and spatial resolution of oceanic measurements, without at the same time sacrificing measurement longevity (Dickey, 1991; Taylor and Howes, *ms. subm.*).

Means for gathering most biological and chemical data have relied upon ship-based approaches which bring the laboratory to the field and operate much like temporary "field stations" for the conduct of research. Such research, however, is restricted in both space and time according to ship availability. Remote sensing techniques (e.g., satellites) increase data coverage but are mostly limited to parameters that can be optically assessed in the surfical water column. Use of moored instrumentation for long-term, high resolution measurements have further addressed some of the limitations of ship-based methodology, but variables within the physical and bio-optical sciences have by-and-large been most successfully applied (e.g., Dickey et al., 1990, 1991; Dickey, 1991; Smith and Waters, 1991). Unfortunately, most of the chemical and biological variables, such as inorganic nutrient concentration and primary production, that one may wish to (a) correlate with physical and biophysical data for understanding the coupling between biological systems and the physical environment, or (b) use for ground-truthing of remote biophysical measurements, are not typically measured at a comparable temporal resolution. Often they are not even within the same one or two orders of magnitude (Taylor and Howes, *ms. subm.)*. The reason is primarily a matter of logistics. Many chemical and biological measurements tend to require physical manipulation, to be labor intensive, and often to require a laboratory setting. Such measurements tend to be controlled as much by the logistical capabilities of the investigator as by the temporal and spatial scales of the environmental changes that may actually be occurring.

Our laboratories have endeavored to reduce the temporal disparity between key chemical and biological measurements, and high resolution physical and biophysical measurements presently being undertaken in oceanography today. To this end we have been working on two lines of autonomous technology. The first, the submersible incubation device (SID) (Taylor and Doherty, 1990), is an automated instrument for performing sequential primary production and other incubation experiments directly in situ. Incubations are performed under conditions that accurately simulate the environment and require no involvement of the investigator other than the analysis of samples at the end of the deployment. The second technical development is an in situ, auto-calibrating continuous flow chemical analyzer (in situ-CFA) for the time-series measurement of three chemical species (initial emphasis, nitrate, phosphate, oxygen). The device is completely autonomous while deployed and is amenable to near real-time data telemetry. Since both instruments automate most of the labor intensive manipulations, it is possible to greatly increase the frequency of measurement in biological and chemical time-series studies.

Production platforms possess capabilities of both shore-based laboratories and long-term moorings and offer a unique opportunity for the application of new automated approaches to time-series measurements in variable environments. In the near term, development, testing and initial long-term deployment of new time-series instrumentation would be greatly benefitted by the frequent periodic technical support and ground-truthing studies made possible by laboratory research facilities that remain in the environment under study for long periods. In the longer term these platforms would provide an ideal base for supporting the regional arrays of instrumented moorings required for synoptic studies of meso-scale physical, chemical, and biological phenomena, and for ground-truthing satellite remote sensors. The SID and in situ-CFA are two automated devices that would interface well with such autonomous moored arrays. We describe herein the capabilities of these automated instruments as applied to the time-series studies of primary production and environmental nutrient status and their advantages over standard techniques.

INSTRUMENTATION

Submersible Incubation Device (SID)

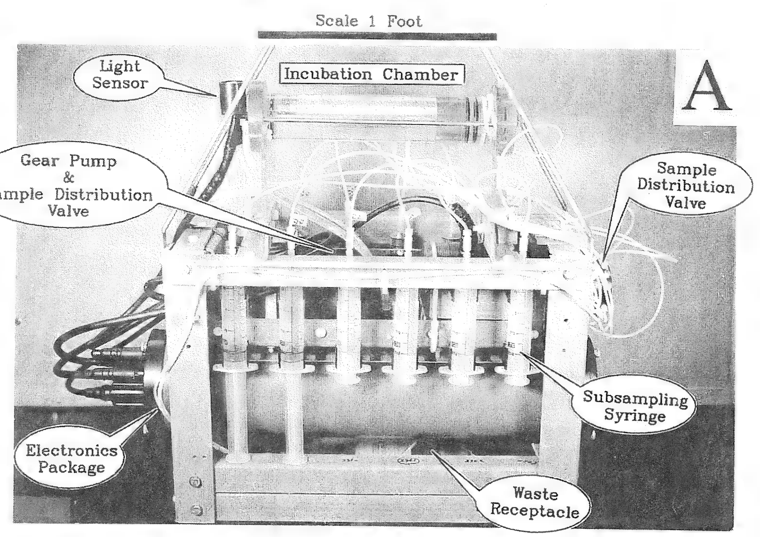
In Situ Incubation

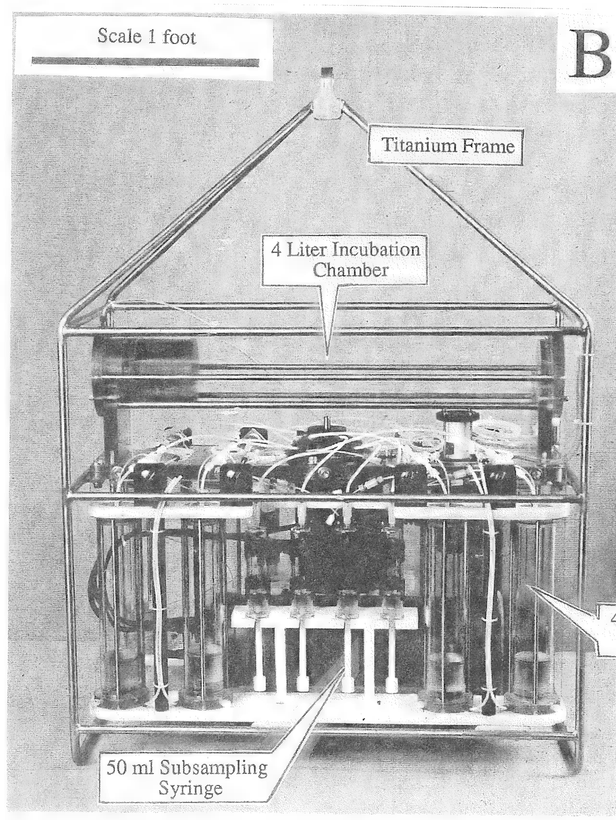
The most accurate means for simulating natural environmental conditions in direct rate measurements is to perform the sample procurement, manipulation, and incubation in situ (Taylor et al., 1983). Because enclosure of a sample within an experimental vessel creates a closed system with properties that will change in time from those of the open environment, sample handling must be performed quickly and gently, and a means for following the progress of the incubation incorporated into the analysis. To this end a multiple incubation SID was built (Taylor and Doherty, 1990) (Figure 1a) with the capacity to perform three sequential time course incubations at user-defined intervals. Each incubation involves a cleaning cycle, procurement of a 400 ml sample at depth with simultaneous introduction of fresh tracer, and the time-course preservation of four 60 ml subsamples for analysis upon retrieval of the instrument (12 subsamples total).

This instrument has been used successfully to conduct in situ phytoplankton production measurements in oligotrophic, shelf, and coastal waters and beneath the permanent ice cover in the Antarctic Dry Valley Lakes. Activities measured have spanned a range of over three orders of magnitude (Taylor and Doherty, 1990). The instrument has been deployed over 50 times for a total of approximately 150 incubations (three incubations per deployment). A larger version SID (4 liter incubation chamber, 400 ml subsamples, Figure 1b) has successfully executed 18 in situ time-course incubations (12 to 18 hr duration) for direct determination of nitrification rates in the Sargasso Sea at depths ranging between 200 and 600 m (O.C. Zafiriou, C.D. Taylor, and L.A. Ball, unpublished results). A new double label technique devised by O.C. Zafiriou and L.A. Ball using $^{15}N^{18}O_2$ will provide some of the first directly measured rates of nitrification where the addition of the tracer does not dramatically alter the nitrite concentration (hence, measured rates) in the incubating sample.

The use of the automated in situ capabilities of the SID has the advantage of avoiding potential artifacts associated with manual measurements. Such was the case in the measurement of photosynthesis in the Antarctic Dry Valley Lakes. In these environments the 24 hr light period, the highly stratified and low intensity light fields within the active euphotic zone, and the influence of photosynthetic pigments on light quality required that all operations of sample procurement, incubation, and fixation occur directly in situ. Classic bottle incubations resulted in overestimates in measured production (Figure 2) because of unavoidable exposure of samples to an "unnaturally" high light field during deployment and recovery of the sample bottles through the 5 m thick ice sheet. The enhanced production observed in the classic

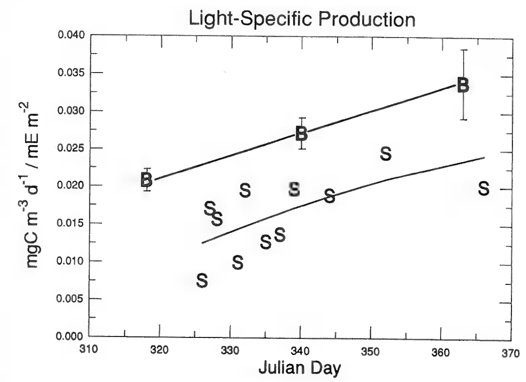
FIGURE 1. Submersible incubation devices (SID). (*a*) Photograph of the SID described by Taylor and Doherty, 1990. (*b*) Photograph of the Deep-SID, a larger version instrument capable of performing microbial rate measurements to depths exceeding 3,000 m. The device is similar in concept and function to the SID. The unit will obtain eight 400 ml subsamples (vertical chambers to right and left) and eight 50 ml subsamples (small, centrally located syringes) from the 4 l incubation chamber (upper horizontal vessel). The device is presently being used for in situ measurement of deep ocean nitrification rates.





bottle versus SID incubations was the result of this brief but unavoidable light exposure. For example, on a typical sunny day in late December the irradiance at 8 m ranged between

FIGURE 2. Comparison of primary production measurements made in 1989 via in situ SID versus bottle incubations in the Antarctic Dry Valley Lake Fryxell. Results of measurements of carbon fixation at 8 m depth (zone of maximum photosynthesis rates) via bottle (B) and SID (S). Light-specific production was computed by dividing 8 m production by the 24 hr integrated light irradiance at 8 m depth. Eleven in situ SID incubations were performed between mid-November and the end of December, spanning the same period covered less frequently by profiling bottle incubations. Error bars, standard deviation of rates obtained by triplicate bottle incubations.



0.5-2 $\mu E\ m^{-2}\ s^{-1}$, while that within the deployment hole in the ice ranged between approximately 150 $\mu E\ m^{-2}\ s^{-1}$ just under the water surface to approximately 16 $\mu E\ m^{-2}\ s^{-1}$ at 4 m. During deployment, the 8 m samples were exposed to approximately 7 minutes of the higher light field as they were lowered and raised in 0.5 m steps in the environment while the upper bottles were being attached to and removed from the mooring line during deployment and recovery. The cumulative light exposure during deployment was approximately 30 mE m^{-2} against a typical 110 mE m^{-2} exposure at depth for a 24 hr period. The result was an exposure of the samples to approximately 27 percent more light than would be experienced by the samples if procured and incubated at depth. The observed artifactual enhancement of carbon production by the bottle incubations versus the SID incubations in late December was not far from this estimate. Hence, in highly stratified light environments the in situ capabilities of the SID permit the investigator to avoid artifacts that would be logistically complex to avoid using classic incubation techniques.

Modes of Incubation

The operational flexibility of the SID has permitted the instrument to be used in a variety of applications. Four modes of SID operation have been implemented so far:

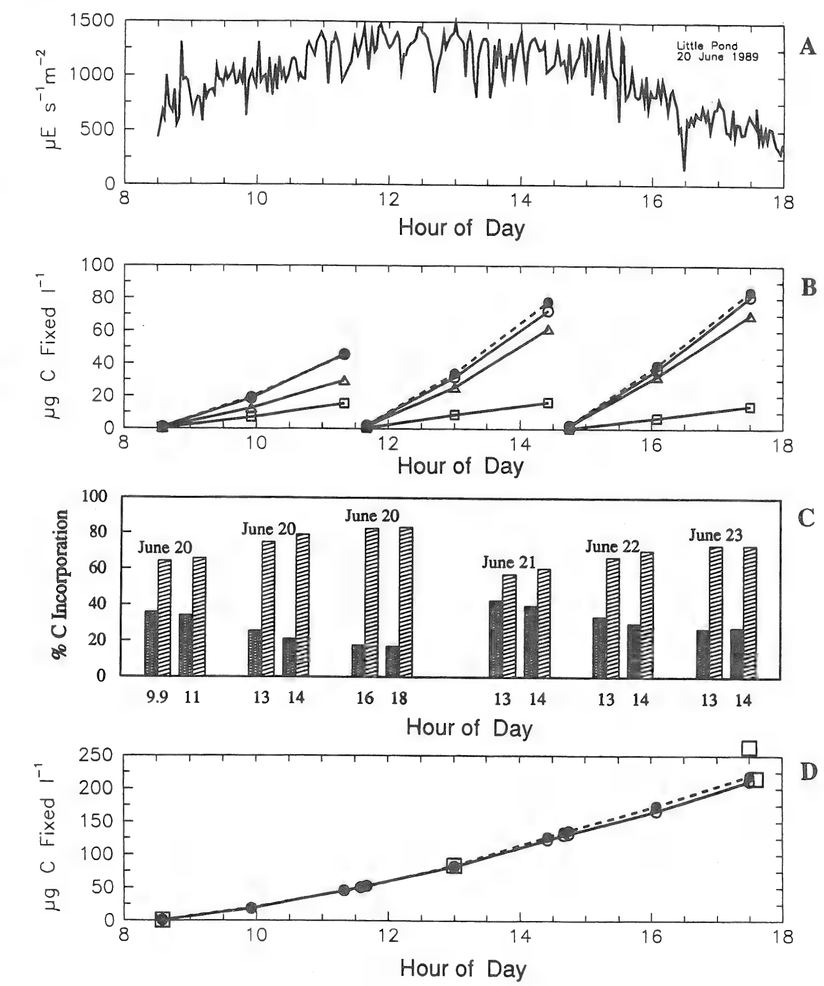
- A back-to-back short-term time-series mode for measurements at a single depth and location in the environment (Taylor and Doherty, 1990) (Figure 3).
- An in situ profiling mode for measurements at three depths during a single deployment (Taylor and Doherty, 1990) (Figure 4).
- An experimental mode for assessing the response of microbial populations to perturbations in environmental conditions (Figure 5).
- A longer term time-series mode where the instrument is left unattended in the environment for several days at a time to provide a high resolution, seasonal composite of photosynthetic activity (Taylor and Howes, *ms. subm.*) (Figure 6).

Back-to-Back Short-Term Rate Measurements

In some environments, such as low nutrient oligotrophic waters or high light intensity surfical waters, the potential for confinement artifacts can be high, especially during the longer term incubations required for some measurements, such as daily primary production. With minimal additional effort, algebraic summation of automated short-term SID incubations (Figure 3b and d) make longer term assessments possible while minimizing confinement and photoinhibition effects. In complex environments, such as frontal regions or coastal systems with significant tidal exchange, site-specific activities will be represented more accurately by a summation of a series of short-term incubations where effects of such things as advection and mixing, or variations in nutrients and phytoplankton populations, are automatically included in the measurement. The approach can also be implemented for calibration of classic techniques that characteristically rely on longer term, end-point incubations (Figure 3d).

Quantification of the distribution of radiotracer among subcellular constituents is also accommodated by SID incubations (Taylor et al., 1983; Lohrenz and Taylor, 1987; Taylor and Doherty, 1990) (Figure 3b and c) and can provide information such as population physiology, composition, and food value. Using this approach, the distribution of newly photosynthetically fixed carbon between low molecular weight metabolites and biopolymers was found to vary significantly throughout the daily light period (Figure 3c) and to vary from day-to-day in a coastal embayment (C.D. Taylor and B.L. Howes, data not shown). On June 20 distribution of ^{14}C-organic carbon into biopolymers ranged between 65 percent of total production in the morning hours to 83 percent by late afternoon. The pattern was evident throughout the June-July period in Little Pond (June 2, 60-78 percent; July 25, 59-89 percent; data not shown) and may reflect a period of replenishment of low molecular weight metabolite pools that have been drawn down by respiration and biosynthesis during the previous dark period (e.g., Goldman et al., 1981; Taylor, unpublished data).

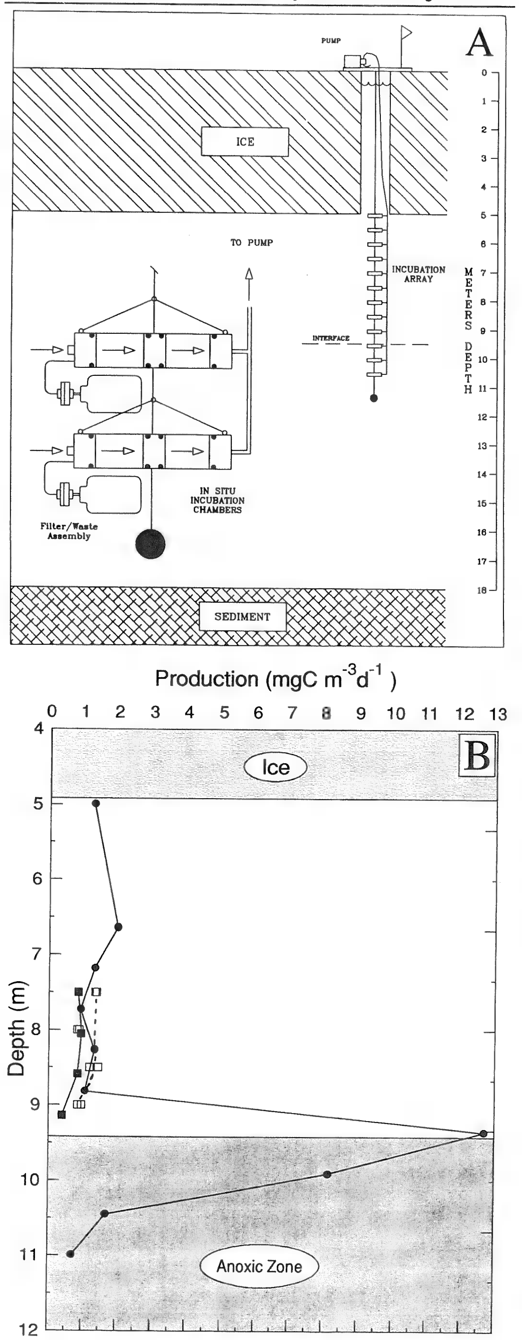
FIGURE 3. Phytoplankton production determined at 0.6 m depth in a coastal embayment, Little Pond, from three 3 hr back-to-back in situ SID incubations and parallel in situ bottle incubations. (*a*) In situ light intensity recorded at 2 min intervals by the SID (2π light sensor). (*b*) Phytoplankton production determined during each of three SID incubations. Open circles, total acid non-volatile ^{14}C-organic carbon production; open triangles, incorporation of ^{14}C-carbon into acid precipitable biopolymers; open squares, incorporation of ^{14}C-organic carbon into low molecular weight metabolites; solid circles and dashed line, total acid non-volatile ^{14}C-organic carbon production (sum of the biopolymer and low molecular weight fractions). Subcellular fractionation was conducted according to the procedure of Lohrenz and Taylor, 1987. (*c*) Percent distribution of newly fixed carbon into low molecular weight metabolites, double hatched bars, and acid precipitable biopolymers, single hatched bars. (*d*) Algebraic summation of the activities measured during the three back-to-back SID incubations to provide a measure of whole-day phytoplankton production, open and closed circles, as above. Open squares represent results of timecourse bottle incubations where samples were obtained from the environment at 8:30 AM and incubated for 4.5 and 9.0 hours.



In Situ Profiling

A common requirement in ecological and biogeochemical studies is a quantitative understanding of rate processes as a function of depth in the water column. Rate profiles can be approximated using a single SID, where the

FIGURE 4. Deployment scheme for manual in situ photosynthesis measurements in shallow aquatic environments. (*a*) In situ profile measurement apparatus based upon multiple incubation chambers (poly-SID). (*b*) In situ primary production profiles in Antarctic Lake Fryxell. Closed symbols, measurements made using the poly-SID on two different measurement dates (closed squares, December 15, 1992; closed circles, December 18, 1992). Classic in situ bottle incubations were also conducted on December 15, 1992, open squares, for comparison with poly-SID measurements made at the same time. Carbon fixation at the oxic-anoxic interface is from chemosynthesis by sulfur-oxidizing bacteria.



instrument is relocated to a different depth in the environment between each of the three possible incubations per deployment (Taylor and Doherty, 1990). Synoptic measurements would require the simultaneous deployment of several instruments. In environments where the euphotic zone resides within approximately the upper 50 m of the water column, simultaneous end-point rate profiles can be obtained using an apparatus constructed of multiple SID incubation chambers (poly-SID) as diagrammatically shown in Figure 4a. The incubation chambers are interconnected in parallel via tubing that is attached to a pump at the surface. To begin in situ incubation the pump is activated to draw sample from the environment by activation of the floating pistons. Tracer is contained within the incubation chamber. At the conclusion of the incubation the pump is activated in the reverse direction to expel incubated sample through an in line filter into a waste container. Samples are analyzed immediately upon retrieval of the apparatus. We have successfully deployed such a device in the Antarctic (Figure 4b) where, as indicated above, because of the unique 24 h light field it is imperative that all aspects of the incubation be executed in situ. Unavoidable brief exposure of bottles to high light intensities resulted in 1.5- to 2-fold increases in measured production relative to poly-SID measurements where all sample manipulation was performed in situ at the depth of incubation.

Experimental Incubations

Multiple incubation capability of the SID also facilitates experimental manipulation of environmental parameters in situ, for example, the assessment of the photosynthetic capacity of phytoplankton residing in the oligotrophic deep chlorophyll maximum (Figure 5). The light within the chlorophyll maximum is an important variable often limiting production within this layer (e.g., Estrada, 1985) and may be potentially influenced by physical phenomena such as the isopycnal doming of the base of the euphotic zone (ca. 20 m) by passage of an eddy (e.g., Falkowski et al., 1991). Investigation of these effects by acquisition of samples for short-term daytime in situ bottle incubations would be subject to artifacts similar to that experienced in the Antarctic and would be logistically complex. In contrast, field light experiments can be conducted using the SID simply by collecting samples at the depth of interest and incubating at a different depth possessing the desired light field. Using this approach, samples procured from the deep chlorophyll maximum in the Sargasso Sea were incubated at shallower depths of higher light intensity. Incubation at a 25-fold higher light intensity, for example, resulted in an *immediate* and sustained 8-fold increase in the rate of photosynthesis. A further ca. 5-fold increase in light produced by incubation at a still shallower depth resulted in photo damage to the shade-adapted cells as evidenced by a 2-fold decreased initial rate of photosynthesis, followed by complete cessation of photosynthesis within 1 hr of exposure. It is clear from these data that the phytoplankton of the deep chlorophyll maximum are photosynthetically active and poised to quickly respond to any increase in in situ light intensity. Given the light gradient in the vicinity of the chlorophyll maximum and the assumption that the phytoplankton population was light limited below the observed 8-fold stimulation, an upward movement of this region by 20 m is projected to result in a stimulation of production by up to 5-fold.

Time-Series Incubations

By modification of the time base of back-to-back SID incubations, it is possible to provide the time-series measurement of a desired parameter on a much longer time scale (months). An illustration of the requirement for high frequency sampling over extended periods is shown by a recent study of phytoplankton production in a near-shore coastal embayment, Little Pond, Massachusetts (Figure 6a) (Taylor and Howes, *ms. subm.*). Whole- and mid-day SID phytoplankton production time-course measurements were conducted at nominal 1-2 d intervals for a nearly four month period in the late spring and summer. Incubation effects were minimal as initial and average rates were coincident in over 90 percent of the 70 production measurements made (solid and dashed lines).

The majority of photosynthetic carbon fixation occurred during a bloom of *Olisthodiscus* in late July through August. Up to two-fold day-to-day differences in production rates that exceeded the experimental error of a typical SID measurement (±23 percent, 2 standard deviations) were found throughout the study. Statistical analyses (stepwise multiple regression) indicated that the variability was in large part due to fluctuations in standing algal biomass as determined by chlorophyll α measurements. Photosynthetic response to a fluctuating light field during periods of light limitation (e.g., wide divergence in photosynthesis rates during a back-to-back incubation during the *Olisthodiscus* bloom; large open circles, Julian day 213) also occurred but was secondary to effects of biomass. Similar two- to three-fold differences in photosynthesis between consecutive days were also found in a study of carbon fixation by a benthic microalgal community (Rizzo and Wetzel, 1986), and three-fold variations between days were observed in a one-month study describing daily photosynthesis in an oligotrophic lake (Cole et al., 1989). There is a growing database suggesting that higher levels of variability in key ecosystem parameters may be more prevalent than typically sensed by classic measurement programs.

An important ecological determination is seasonal or annual primary production, a parameter that is typically obtained by integration, over time, of depth-integrated production. In Little Pond 63 gC m^{-2} was produced during a 108 day period during summer (Figure 6b, heavy dashed line). In order to investigate effects of sampling frequency upon seasonal primary production (Taylor and Howes, *ms. subm.*), downsampling routines were executed on the high

FIGURE 5. Photosynthesis rates of oligotrophic samples obtained from the chlorophyll maximum by the SID and incubated at various light intensities. (*a*) Surface light intensity measured by a 2π light sensor. (*b*) In situ light intensity recorded by the SID (2π light sensor). Values in the body of the figure are relative light intensity levels expressed as percent subsurface light and the resultant fold increase in light intensity between the first and second incubations. (*c*) Depth of the SID throughout the deployment (solid line), and relative in vivo fluorescence at indicated depths (dashed line). Large closed squares indicate the depth of sample procurement prior to incubation. In two of the three incubations the depth of incubation was less than the depth of sample procurement. (*d*) Carbon fixed during the three incubations.

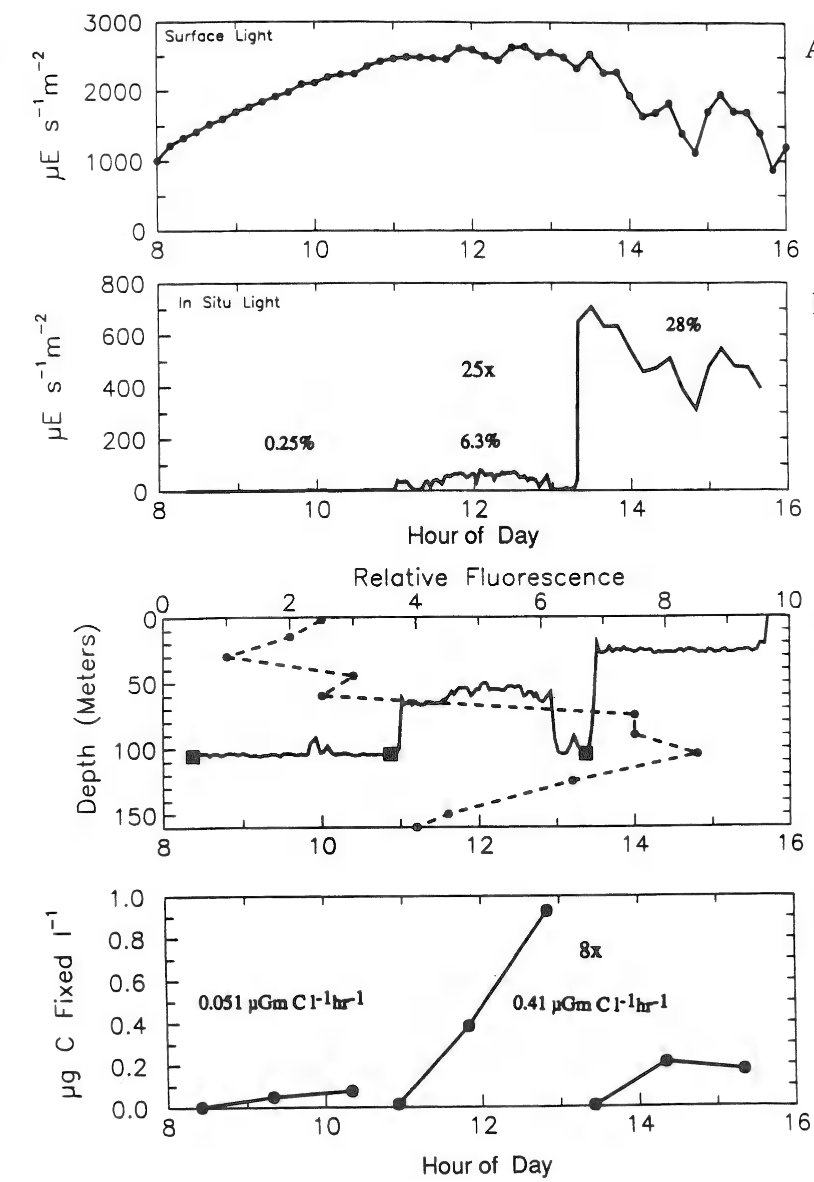
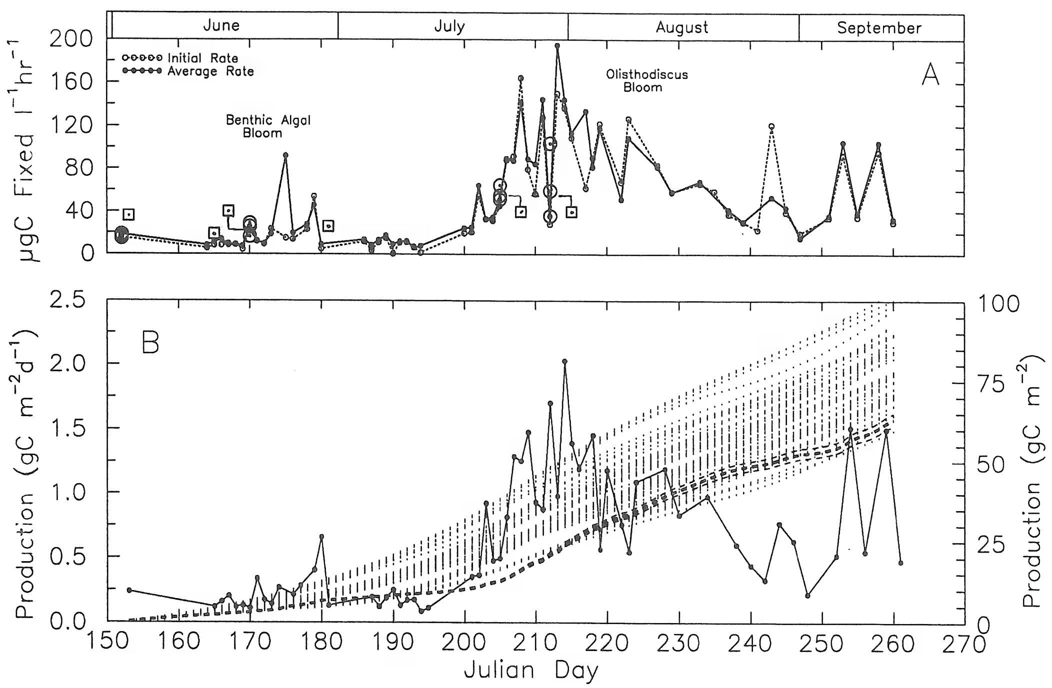


FIGURE 6. Photosynthesis in a coastal embayment, Little Pond, Massachusetts. (*a*) Photosynthesis rates determined from approximately 23 SID deployments comprising 70 incubations, and six-time course in situ bottle incubations. Small open circles and dashed line, initial photosynthesis rates determined from the first 1.5 hrs of the incubation; small closed circles and solid lines, rates determined from the full 3 hr incubation; large open circles with central dot, morning, mid-day, and afternoon photosynthesis rates determined from three 3 hr, back-to-back SID incubations as illustrated in Figure 3d; large open squares with central dot, photosynthesis rates determined from in situ bottle incubations. (*b*) Small circle is depth integrated phytoplankton production at Little Pond during summer; dashed line is cumulative phytoplankton production and associated error caused by the ± 23 percent uncertainty (coefficient of variation * 2) in SID measurements; dotted line is cumulative production from data obtained by the repeated down-sampling of the high resolution data set at nominal 28 ± 2 d intervals. The down-sampling and integration procedure was repeated 50 times to simulate results obtained if that many independent laboratories made measurements at the indicated nominal intervals.



temporal resolution data set (Figure 6b, solid line) and cumulative carbon fixation was computed using the lower resolution "sampling". To simulate a real sampling program a variability of ± 2 days was randomly associated with the time base to provide a data set with a "nominal" sampling interval of 28 days. Repetition of the down-sampling and integration process (50 times, dotted lines) indicated that the sampling frequencies commonly employed in ecosystem studies significantly degrade the accuracy of seasonal production measurements when compared with data obtained at 1-2 day intervals (heavy dashed line). Measurements made at nominal 28-day intervals yielded summer production ranging between 59 and 100 gC m^{-2}, a potential 1.7-fold variation in activity simply based upon the sequence of days that the incubations were conducted. In addition, production estimates determined from the assemblage of 50 down-sampled data sets did not center upon the seasonal production value found from the high resolution data (63 gC m^{-2}), but possessed a mean (77 ± 20 gC m^{-2}, standard deviation *2) that was biased high by 22 percent. Depending upon the sampling interval employed, biases of this nature resulted in mean overestimates of up to 25 percent and underestimates to 16 percent, when nominal sampling intervals (e.g., >20 days) begin to approach the temporal scale of major activity events such as the summer bloom (approximately 50 days in Little Pond). Errors in computed seasonal production diminish as the frequency of sampling increases, but it is not until sampling intervals of 5 days or less that sampling frequency-induced error began to approach the limit of the method.

An important message from the Little Pond study is that time-series measurements at the temporal resolution typically employed in long-term studies disobey the classic rules of sampling theory (Chatfield, 1984). Intensive sampling in the traditional sense (14-30 d intervals) includes significant error and is inadequate for the quantitative studies necessary for determining the linkages between physico-chemical processes and biological response. One solution is to emphasize new instrumental approaches, such as automated incubation techniques, that can attain the required high frequency data without the concomitant increases in logistical costs that would result from intensified sampling using traditional methods.

Extended Deployment Time Series-Submersible Incubation Device (TS-SID)

With a capability of only 3 or 4 unattended incubations, use of the SID for routine high resolution time-series studies over extended periods (months) is still labor intensive. Long-term time-series studies are better accommodated by extending the basic procedures conducted by the SID to allow many more incubations, thus increasing the deployment period from a few hours or days to months. For long-term deployments modifications to the SID concept are necessary:

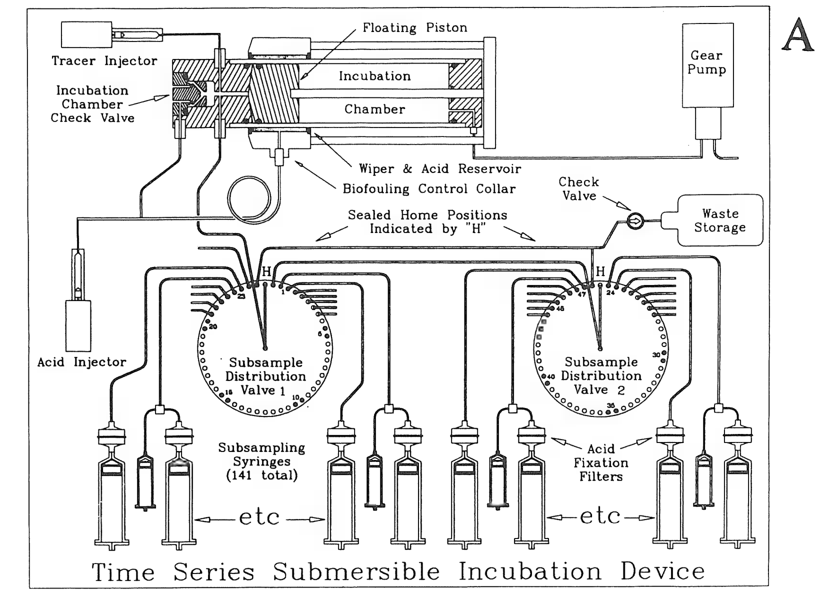
- Valving to permit more subsamples to be taken.
- A means for the repeated and accurate introduction of tracer into the sample to be incubated.
- A means for the control of biofouling on the internal and external surfaces of the instrument.

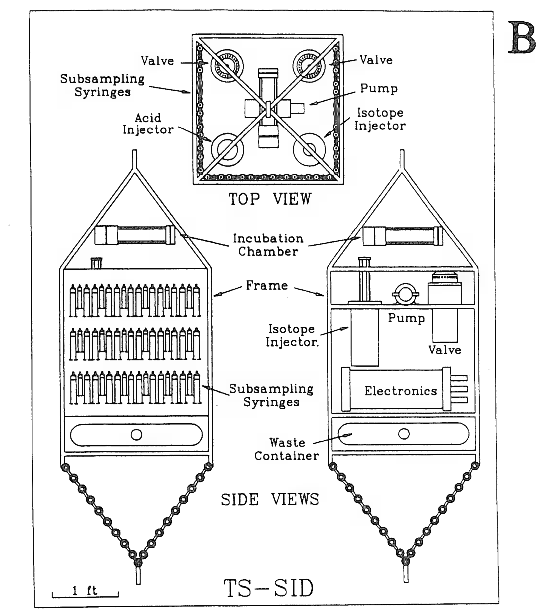
A prototype TS-SID that incorporates these major features is near completion and is diagrammatically illustrated in Figures 7a and b. The device is capable of conducting 47 in situ end-point incubations (to, t1) or 31 three-point time-course incubations (to, t1, t2) at user determined intervals. During each deployment a total of 94 subsamples will be preserved for subsequent analysis.

The overall mechanical operations performed during a typical incubation by the TS-SID will be similar to those of the SID. Major operational differences in the new instrument are the use of "smart" sample distribution valves (SDV) for fluid control and "active" electromechanical introduction of tracer. To reserve as many valve positions as possible for subsampling operations, only a single port on each valve will be used for sample inlet and waste management (Figure 7a) in contrast with the multiport execution of these functions in the standard SID (Taylor and Doherty, 1990). The SDVs will operate bidirectionally from a sealed "home" position during flushing, sample procurement, and subsampling operations.

Tracer (up to approximately 0.5 ml) will be quantitatively introduced into the incubation chamber by the activation of the 30 ml tracer injector for approximately 50 percent of the sample procurement cycle. Gentle turbulence within the incubation chamber mixes the tracer with the incoming sample. When the chamber is filled incubation commences.

FIGURE 7. Schematics of the TS-SID. (*a*) Major operational components. Mechanical operations performed during a typical incubation by the TS-SID are similar to those of the SID (Figure 1a, Taylor and Doherty, 1990). (*b*) Arrangement of modules within a mooring-strength titanium frame. Side view left, view showing subsampling array; side view right, subsampling array removed to show location of major components.





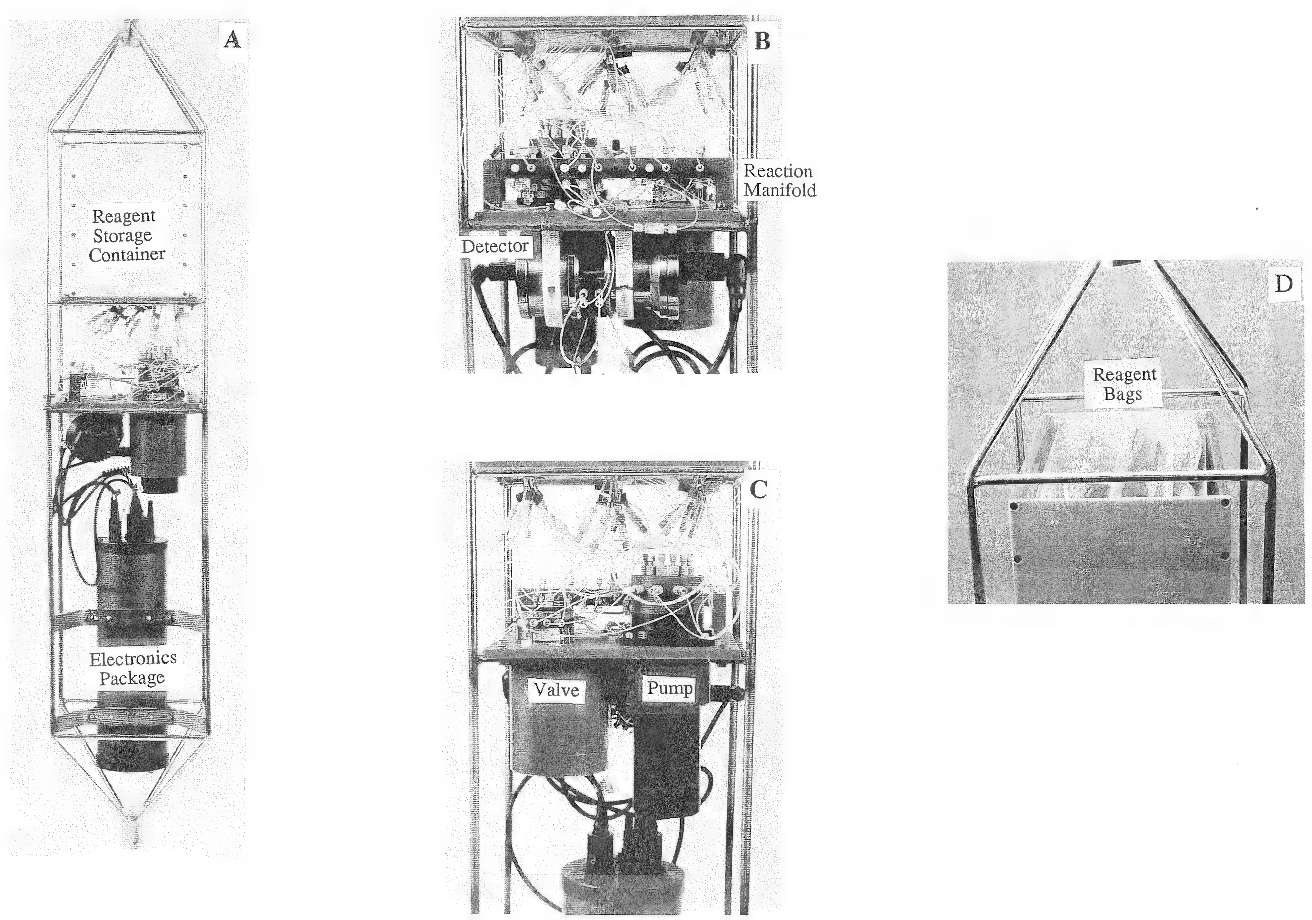
At user specified intervals subsamples are expelled from the incubation chamber, through one of the SDVs, into a subsampling syringe. Biological activity is terminated by an acid fixative contained within the subsampling syringes or by passage of sample through special in line filters that permit subsequent acid fixation (arrangement shown). Zero-time subsamples are also collected in smaller syringes containing an alkaline fixative for determination of tracer specific activity in the incubation cham-

ber. During the first half of the deployment, SDV-2 will remain quiescent in the "home" position until all of the subsamples controlled by SDV-1 have been taken. During the remainder of the deployment the valves are activated for distribution of subsamples into the remaining banks of subsampling syringes. To conserve power the TS-SID computer shuts off the pump as soon as the pistons in the incubation chamber or subsampling syringes have reached the full extent of their desired travel.

When a given incubation is completed the remaining volume of sample in the incubation chamber is expelled into a flexible waste container (capacity 20 liters) and the chamber flushed 2 to 3 times in preparation for the next incubation (waste into the storage container). For protection against internal and external biofouling an acid injector identical to the tracer injector except for size (300 ml syringe) is implemented. At specified intervals, dilute acid is introduced into the incubation chamber in much the same way that tracer is introduced. Acidified seawater is distributed from the incubation chamber to the SDVs and sample inlet for internal biofouling control. Prior to the next incubation, the acidified water is flushed from the system via the acid flushing port.

Protection from external biofouling and collection of light-occluding particulate material upon the incubation chamber outer wall is effected by an acid-containing external sleeve that is mechanically coupled to the incubation chamber piston. Movement of the floating piston during normal filling and subsampling continuously removes particulate material and repeatedly exposes the chamber outer surface to low pH. Replenishment of acid is effected by tubing connected to the acid injector. This time-series instrument is presently undergoing laboratory and field testing.

FIGURE 8. Photographs of in situ-CFA and major components. (*a*) Entire unit (width of frame, 14 in); (*b*) Close-up of detector; (*c*) Close-up of sample-standard distribution valve and three channel piston pump; (*d*) Reagent bags in reagent storage container (top lid removed).

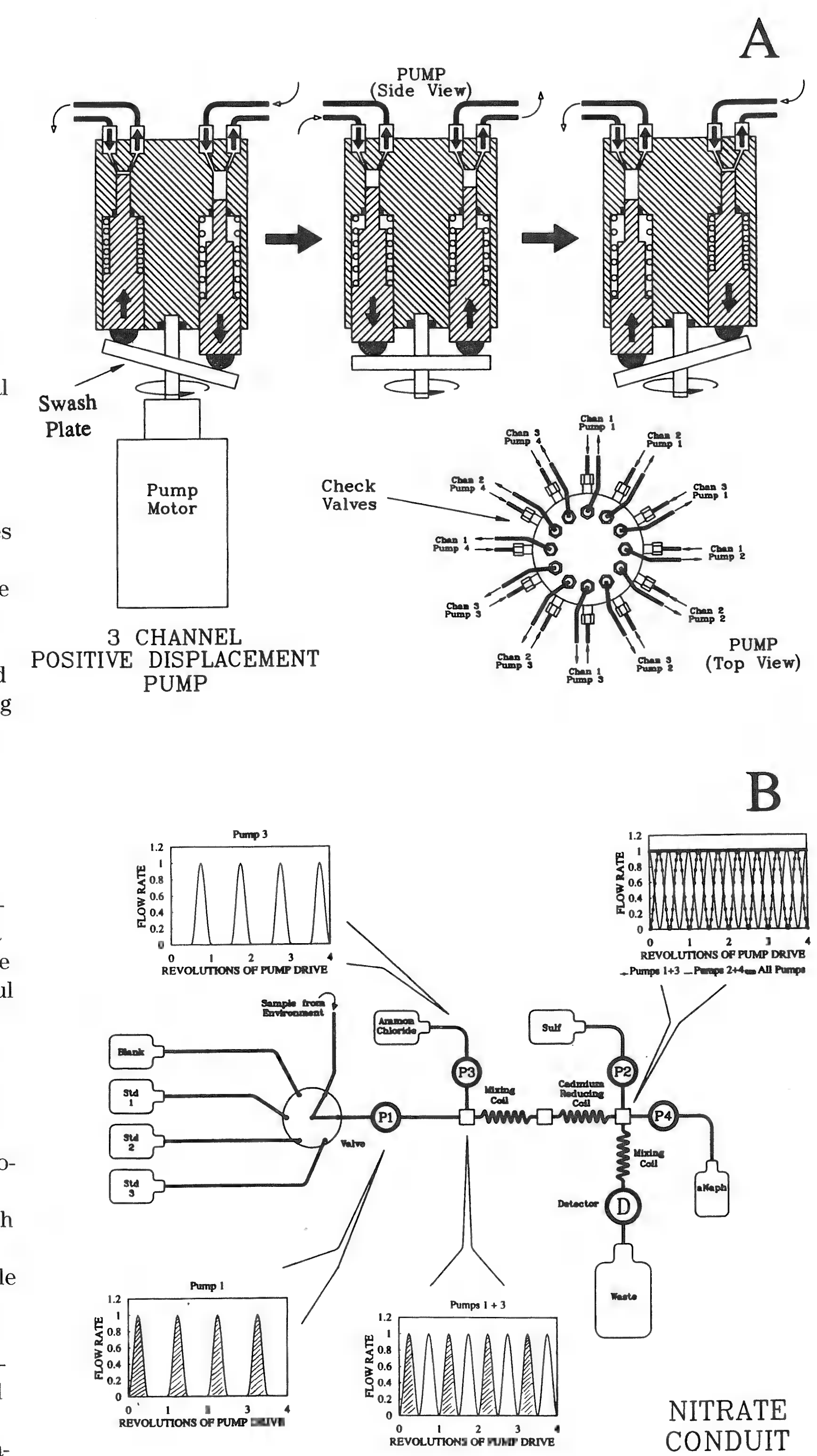


In Situ Continuous Flow Chemical Analyzer (In Situ-CFA)

A nearly universal requirement of research in chemical, biological, and some aspects of physical oceanography is the measurement of the concentration and distribution of chemical species in the oceanic water column, particularly the inorganic micronutrients. Usual approaches for quantifying such compounds in seawater entail the acquisition of discrete samples from the environment and chemical analysis (e.g., Strickland and Parsons, 1972; Grasshoff, 1976) using manual or continuous flow autoanalysis (CFA) in shipboard or land-based laboratories. Hence, many of the temporal limitations inherent in classic biological measurements are also operative in the measurement of ocean chemistry.

A promising step in marine analytical chemistry has been the application of techniques of flow injection analysis (FIA) (Ruzicka and Hansen, 1981; Ruzicka and Hansen, 1988) for the development of automated chemical analyzers that operate in situ (Johnson et al., 1986a, b; 1989). Our laboratories have recently completed construction on a three-channel in situ operating CFA (in situ-CFA; Figure 8). The basic principle employed in the in situ-CFA is the precision introduction of sample into narrow bore tubing (inside diameter, 0.5 mm) containing a flowing stream of a suitable liquid or reagent. As the sample is transported through the tubing, it is dispersed in a reproducible fashion into the carrier stream where it chemically reacts to form a product that can be quantified by an appropriate detector. An absolute requirement for successful use of an autonomously functioning CFA is an accurate and completely reliable reagent and sample delivery system. To that end we have implemented a three-channel positive displacement piston pump that is patterned in concept after those used in high performance liquid chromatography (HPLC) and capable of delivery of fluids against a substantial flow resistance. Each channel consists of four pump heads that are responsible for delivery of each of three possible reagents and sample (or standard). Each 10 μl pump head is operated at 30 to 60 strokes per min by a rotating swash plate as illustrated conceptually in Figure 9a. Though each pump head produces a truncated sinusoidal "pulsed" flow (pump 1, pump 3 insets, Figure 9b), the 90° relative placement of each of the four heads of a given channel (top view, Figure 9a) provides a constant flow when the four outputs are combined within a typical reaction conduit (Figure 9b and insets). The alternating sinusoidal fluctu-

FIGURE 9. Diagrammatic representation of major components of the in situ-CFA. (*a*) Submersible three-channel positive displacement piston pump used for reagent and sample delivery. (*b*) Reaction conduit for nitrate analysis. P1-P4, pump heads 1-4 of one of the three channels (see also a); Sulf, sulfanilamide reagent; aNaph, α-naphthylethylenediamine reagent. Inserts, flow characteristics at the indicated locations within the conduit.

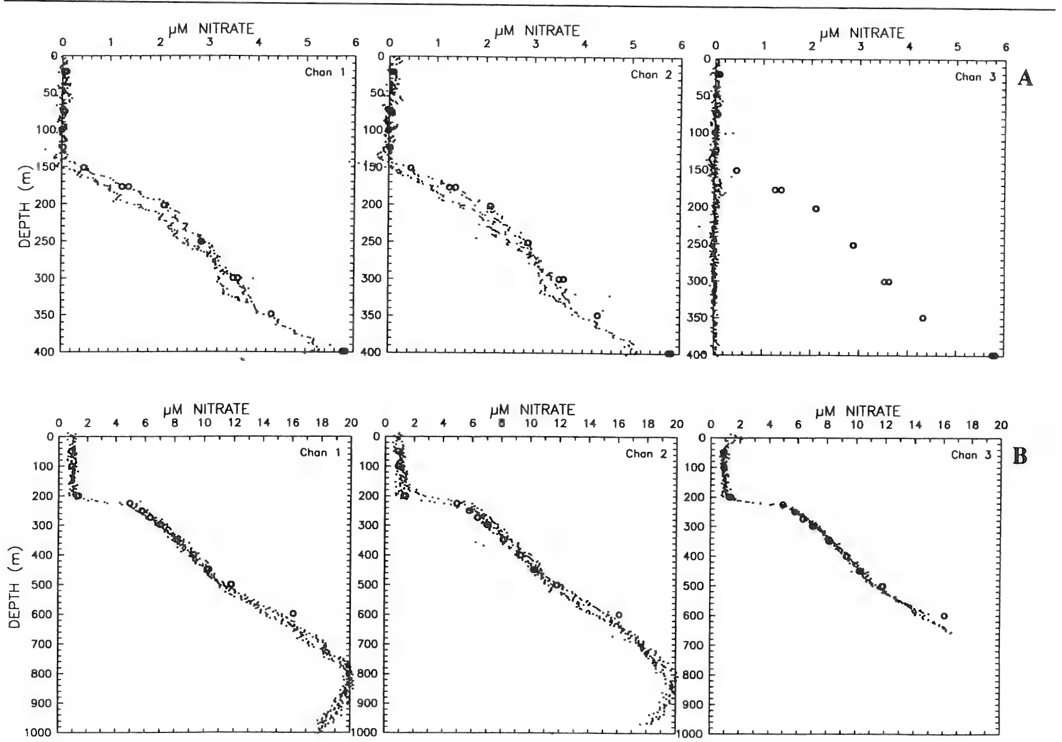


ation in reagent composition (hatched areas in pump 1 + 3 inset, Figure 9b) is thoroughly mixed by laminar flow dispersion and radial diffusion within the mixing coils. At specified intervals sample analysis is temporarily interrupted for calibration by the sequential introduction of reference standards via a calibration valve (Figure 9b).

Two characteristics of detector output relative to the time-dependent concentration of the analyte entering the conduit are (a) a delay (td, min) resulting from the time required for sample to flow through the reaction conduits to the detector and (b) an exponential response (time constant of k, min^{-1}; time to come within 99 percent of steady state, $t_{99} = \ln[0.01]/k$) to changing analyte concentration, due to smearing of the sample zone via laminar flow dispersion (Ruzicka and Hansen, 1988). During profiling the effect of td is to displace the resultant data profile several meters (determined as $t_d \times V$, where V is the deployment velocity [m min^{-1}]) below or above its true location in the downcast and upcast, respectively. The effect of k is to low pass filter the data stream, and the degree to which the data are distorted depends upon how quickly the concentration of the incoming analyte is changing. In the oceanic environment this will be a function of the depth-dependent analyte concentration gradient and the deployment velocity of the instrument.

Examples of nitrate profiles to depths of 1,000 m obtained by the instrument deployed at 20 m min^{-1} are shown in Figure 10. Data were corrected for effects of t_d (approximately 1.7 min) but not for effects of k (approximately 2.8 min^{-1}), since at the deployment rates employed, the data were not largely affected. Faster deployment rates would, however, necessitate the application of digital algorithms to extract a more accurate approximation of the true analyte profile. Results from the in situ-CFA operating in a profiling mode show excellent agreement with measurements made on samples obtained via a shipboard CTD-rosette sampler. The ability to independently alter the sensitivities of each channel (e.g., Figure 10b, channel 3) will permit analyses over a wide dynamic range, as might be required in highly stratified environments (e.g., Black Sea) or in systems with large temporal variations in chemical composition.

FIGURE 10. Comparison of nitrate profiles in the Sargasso Sea near Bermuda determined by the in situ-CFA versus standard shipboard analysis. Small dots are analyses made by the prototype in situ CFA; open circles are shipboard analyses of samples obtained by CTD-Nisken casts taken at the same location. Data from CFA up-and down-casts are shown, and were corrected for effects of analysis delay (t_d, see text for explanation). All three channels of the instrument were set up for the analysis of nitrate. (*a*) Profiles obtained on January 25, 1992, in the Sargasso Sea south of Bermuda (25°51'0" N, 67°33'1" W). Channel 3 was set up for the analysis of blank during the deployment. (*b*) Profiles obtained on January 30, 1992, in the Sargasso Sea north of Bermuda (34°16'7" N, 68°14'1" W). The gain of the channel 3 detector was set to a higher sensitivity than the other channels. Detector output exceeded the range of the AD converter when the nitrate concentration was greater than approximately 17 μM, hence, the truncated profile.



In contrast to the continuous mode described above, the time-series application of the instrument (TS-CFA) can provide chemical measurements at a fixed location in the environment over long periods. In this mode the instrument would remain quiescent for most of the time and, at specified intervals, would be activated to conduct a self-calibration and analysis of the species of interest. Since the in situ-CFA was originally designed to be operated in either the continuous or time-series mode, major changes in mechanics or electronics are not necessary for time-series applications. The major engineering issue to be addressed will be the biofouling protection of the sample inlet of the instrument to avoid potential for biofilm uptake of nutrients from the sample when entering the reaction conduit. The instrument is presently undergoing time-series testing.

CONCLUSIONS

We have addressed new instrumentation for the automated in situ measurement of rates of photosynthesis and other microbial processes and for assessment of micronutrient pools in coastal and oceanic environments. High resolution time-series studies of photosynthesis using the SID have indicated that the standard sampling interval commonly employed in coastal and oceanic studies can lead to significant errors in the interpretation of the temporal patterns of photosynthesis and quantification of integrated measures of production expressed on a seasonal or annual basis. SID technology may be used in a variety of field applications, substantially reduces sampling artifacts of standard techniques, and with the in situ-CFA, is compatible with remote deployment over long periods of time. Both SID and in situ-CFA instruments, when incorporated into regional arrays of automated moorings supported by offshore platform research programs, should greatly facilitate the gathering of time-series data for sensing temporal and spatial variability in coastal and oceanic ecosystems and for understanding meso-scale interactions between physical, chemical, and biological phenomena occurring in these environments.

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REFERENCES

Bisagni, J.J. 1992. Differences in the annual stratification cycle over short spatial scales on southern Georges Bank. *Continental Shelf Res.* 12, 415–435.

Chatfield, C. 1984. The Analysis of Time Series: An Introduction. New York: Chapman and Hall. 131 pp.

Cole, J.J, Caraco, N.F., Strayer, D.L., Ochs, C. and Nolan, S. 1989. A detailed organic carbon budget as an ecosystem-level calibration of bacterial respiration in an oligotrophic lake during midsummer. *Limnol. Oceanogr.* 34: 286–296.

Dickey, T.D. 1990. Physical-optical-biological scales relevant to recruitment in large marine ecosystems, p. 82–98. In: *Large Marine Ecosystems, Patterns, Processes, and Yields.* K. Sherman, L.M. Alexander, and B.D. Gold [eds]. Washington, D.C.: American Association for the Advancement of Science.

Dickey, T.D. 1991. The emergence of concurrent high-resolution physical and bio-optical measurements in the upper ocean and their applications. *Rev. Geophys.* 29: 383–412.

Dickey, T., Granata, T., Hamilton, M., Wiggert, J., Marra, J., Langdon, C. and Siegel, D.E. 1990. Time-series observations of bio-optical properties in the upper layer of the Sargasso Sea. *Ocean Optics.* 10, 202–214.

Dickey, T., Marra, J., Granata, T., Langdon, C., Hamilton, M., Wiggert, J., Siegel, D. and Bratkovich, A. 1991. Concurrent high resolution bio-optical and physical time-series observations in the Sargasso Sea during the spring of 1987. *J. Geophys. Res.* 96, 8643–8663.

Dustan, P. and Pinckney, J.L. Jr. 1989. Tidally induced estuarine phytoplankton patchiness. *Limnol. Oceanogr.* 24: 410–419.

Estrada, M. 1985. Primary production at the deep chlorophyll maximum in the Western Mediterranean. In: *Proceedings of the 19th European Marine Biology Symposium*, Plymouth, Devon U.K, 16–21 September 1984. P.E. Gibbs, ed, Cambridge University Press. pp. 109–121.

Falkowski, P.G, Zieman, D., Kolber, Z. and Beinfang, P.K. 1991. Role of eddy pumping in enhancing primary production in the ocean. *Nature.* 352, 55–58.

Goldman, J.C., Taylor, C.D. and Gilbert, P.M. 1981. Nonlinear time-course uptake of carbon and ammonium by marine phytoplankton. *Mar. Ecol. Progr. Ser.* 6, 137–148.

Grasshoff, K. 1976. Methods of seawater analysis. Weinheim, N.Y.:Verlag Chemic. 317 p.

Horne, E.P.W., Loder, J.W., Harrison, W.G., Mohn, R., Lewis, M.R., Irwin, B. and Platt, T. 1989. Nitrate supply and demand at the Georges Bank tidal front. In: *Proceedings of the 22nd European Marine Biology Symposium.* J.D. Ros, ed, Scientia Marina, v. 53. pp. 145–158.

Jenkins, W.J. and Goldman, J.C. 1985. Seasonal oxygen cycling and primary production in the Sargasso Sea. *J. Mar. Res.* 43: 465–491.

Johnson, K.S., Beehler, C.L. and Sakamato-Arnold, C.M. 1986a. A submersible flow analysis system. *Anal. Chim. Acta.* 179, 245–257.

Johnson, K.S, Beehler, C.L. and Sakamato-Arnold, C.M. 1986b. In situ measurements of chemical distributions in a deep-sea hydrothermal vent field. *Science.* 231,1139–1141.

Johnson, K.S., Sakamoto-Arnold, C.M. and Beehler, C.L. 1989. Continuous determination of nitrate concentrations in situ. *Deep-Sea Res.* 36, 1407–1413.
Lewis, M.R. and Platt, T. 1982. Scales of variability in estuarine ecosystems. p 3–20. In: *Estuarine Comparisons.* V.S. Kennedy [ed]. New York: Academic Press.
Lohrenz, S.E. and Taylor, C.D. 1987. Primary production of protein: I. Comparison of net cellular carbon and protein synthesis with ^{14}C-derived rate estimates in steady-state cultures of marine phytoplankton. *Marine Ecology Progress Series.* 35, 277–292.
Lohrenz, S.E., Knauer, G.A., Asper, V.L., Tuel, M., Michaels, A.F. and Knap, A.H. 1992. Seasonal variability in primary production and particle flux in the northwestern Sargasso Sea: U.S. JGOFS Bermuda Atlantic Time-Series Study. *Deep-Sea Res.* 39: 1373–1391.
Lohrenz, S.E., Taylor, C.D. and Howes, B.L. 1987. Primary production of protein. II. Algal protein metabolism and its relation to particulate organic matter decomposition in the surface mixed layer. *Mar. Ecol. Progr.* Ser. 40: 175–183.
Marra, J., Bidigare, R.R. and Dickey, T.D. 1990. Nutrients and mixing, chlorophyll and phytoplankton growth. *Deep-Sea Res.* 37, 127–143.
Michaels, A.F., Knap, A.H., Dow, R.L., Gundersen, K., Johnson, R.J., Sorensen, J., Close, A., Knauer, G.A., Lohrenz, S.E., Asper, V.A. and Tuel, M. In press. Ocean time-series measurements off of Bermuda: The first two years of the U.S. JGOFS Bermuda Atlantic Timer-Series Study. *Deep-Sea Res.*
Mills, D.K. and Tett, P.B. 1990. Use of a recording fluorometer for continuous measurement of phytoplankton concentration. In: SPIE Proceedings: *Environment and Pollution Measurement Sensors and Systems.* 1269:106–115. Bellingham, WA: Society for Photo Optical Instrumentation Engineers.
Nixon, S.W., Oviatt, C.A., Frithsen, J. and Sullivan, B. 1986. Nutrients and the productivity of estuarine and coastal marine ecosystems. *J. Limnol. Soc.* South Africa. 12: 43–71.
O'Reilly, J.E. and Busch, D.A. 1984. Phytoplankton primary production on the northwestern Atlantic shelf. Rapp. P.v. Reun. Cons. int. Explor. Mer. 183,255–268.
O'Reilly, J.E, Evans-Zetlin, C. and Busch, D.A. 1987. Primary production. In: *Georges Bank.* R.H. Backus [ed]. Cambridge, MA: MIT press. pp. 220–233.
Rizzo, W.M. and Wetzel, R.L. 1986. Temporal variability in oxygen metabolism of an estuarine shoal sediment. In: *Estuarine Variability.* D.A. Wolfe [ed]. New York: Academic Press. p 227–239.
Ruzicka, J. and Hansen, E.H. 1981. Flow injection analysis. In: *Chemical Analysis.* P.J. Elving and J.D. Winefordner, [eds]. New York: John Wiley & Sons. 207 p.
Ruzicka, J. and Hansen, E.H. 1988. Flow injection analysis. In: *Chemical Analysis.* J.D. Winefordner, [ed]. New York: John Wiley & Sons. 498 p.
Sanford, L.P., Sellner, K.G. and Breitburg, D.L. 1990. Co-variability of dissolved oxygen with physical processes in the summertime Chesapeake Bay. *J. Mar. Res.* 48: 567–590.
Smith, R.C. and Waters, K.J. 1991. Optical variability and pigment biomass in the Sargasso Sea as determined using deep-sea optical mooring data. *J. Geophys. Res.* 96, 8665–8686.
Strickland, J.D. and Parsons, T.R. 1972. A practical handbook of seawater analysis. *Bull. Fish. Res. Bd. Can.* 310 pp.
Taylor, C.D. and Doherty, K.W. 1990. Submersible Incubation Device (SID), autonomous instrumentation for the in situ measurement of primary production and other microbial rate processes. *Deep-Sea Res.* 37: 343–358.
Taylor, C.D., Molongoski, J.J. and Lohrenz, S.E. 1983. Instrumentation for the measurement of phytoplankton production. *Limnol. Oceanogr.* 28, 781–787.
Taylor, C.D. and Howes, B.L. *ms. subm.* Effect of sampling frequency on measurements of seasonal primary production and oxygen status in near-shore coastal ecosystems.
Walsh, J.J, Whitledge, T.E., O'Reilly, J.E., Phoel, W.C. and Draxler, A.F. 1987. Nitrogen cycling on Georges Bank and the New York shelf: A comparison between well-mixed and seasonally stratified waters. In: *Georges Bank.* R.H. Backus, [ed]. Cambridge, MA: MIT press. pp. 234–246.

PAPER

Flower Gardens Ocean Research Project: Using Offshore Platforms as Research Stations

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ABSTRACT

The Flower Gardens Ocean Research Project (FGORP) is a cooperative program between Mobil Exploration and Producing U.S. Inc. (MEPUS) and British Petroleum Inc. (BP), and a consortium of marine research and resource management professionals. MEPUS and BP allow researchers working in the northwest Gulf of Mexico to use oil and gas production platforms as research stations, providing transportation to and from the platforms and room and board for research personnel.

To date, studies of larval recruitment, artificial reef productivity, coral reproduction, audio/video survey technology, and continuous real-time monitoring of sea level have been conducted at Mobil platform HI-A389A (27°54'30" N, 93°35'06" W). In addition, Mobil HI-A389A has been used as a base station from which to train field technicians in advanced diving and underwater visual survey techniques.

Currently, the feasibility of converting Mobil HI-A389A to a full-time research and training station when its gas production function is completed is being investigated. Surveys of Gulf Coast research and resource management professionals indicate that there is a need for year-round direct access to the marine environments of the outer continental shelf, such as could possibly be provided by a full-time offshore research station.

INTRODUCTION

The National Research Council (1992) reported that funding for marine science has not kept pace with need, and innovative new strategies will be necessary to meet the challenge of achieving a better understanding of the oceans. The Flower Gardens Oceans Research Project (FGORP) is an example of one such program, joining the physical and financial resources and professional expertise of industry and marine research professionals.

FGORP began in 1990 when Mobil Exploration and Producing U.S. Inc. (MEPUS) agreed to provide support to marine research scientists working in the northwest Gulf of Mexico. MEPUS offered to (1) allow researchers to use Mobil production platforms as research stations, (2) provide transportation to and from the platforms, and (3) provide room and board for the research personnel stationed on the platforms. Recently, British Petroleum Inc. (BP) has made available three BP platforms for marine research applications.

Oil and gas production platforms represent a unique opportunity to expand offshore marine research. Since the structures are made of steel and are semipermanent, they afford the opportunity to mount oceanographic and meteorological monitoring equipment for the collection of long-term data as well as provide stable foundations from which to conduct hands-on studies.

In the early 1970s, Gulf of Mexico researchers pursued the concept of platform-based research (T. Bright, personal communication). More recently, the feasibility of converting a semi-submersible drilling platform to a deep-sea observatory (DSO) was the focus of a workshop sponsored by Scripps Institution of Oceanography and Woods Hole Oceanographic Institution (DSO Workshop, 1990). The collection of meteorological data via instrumentation mounted on platforms in the Gulf of Mexico is being investigated by Lewis (1993). The possibility of establishing a global network of meteorological stations on offshore production platforms is being explored by the National Oceanographic and Atmospheric Administration's Office of Global Change (Busch, 1993).

There are approximately 3,800 oil and gas production platforms operating in the Gulf of Mexico. These are primarily concentrated off Louisiana and Texas. Recent activities suggest that future installations of production platforms will expand the distribution of platforms into deeper waters of the continental shelf and slope.

A continuous real-time current monitoring network extending from the shore to the deeper waters of the outer continental shelf would be invaluable in tracking and predicting movement of oil spills. Further, vertical stratification of currents in the northwest Gulf is common, often with the stratified currents flowing in opposing directions at differing speeds. Real-time current meters installed at varying water depths would allow predictions of the location at which oil leaking from a source on the seabed would reach the surface.

Conceptually, a grid of selected platforms across the Gulf could serve to support studies that historically have occurred infrequently and for limited duration because of marine vessel requirements. Research aboard marine vessels is affected by weather conditions, and vessel cost—typically ranging from $3,000 to $5,000 per day and consuming

50 percent or more of the total project budget—is a major expense of conducting offshore research.

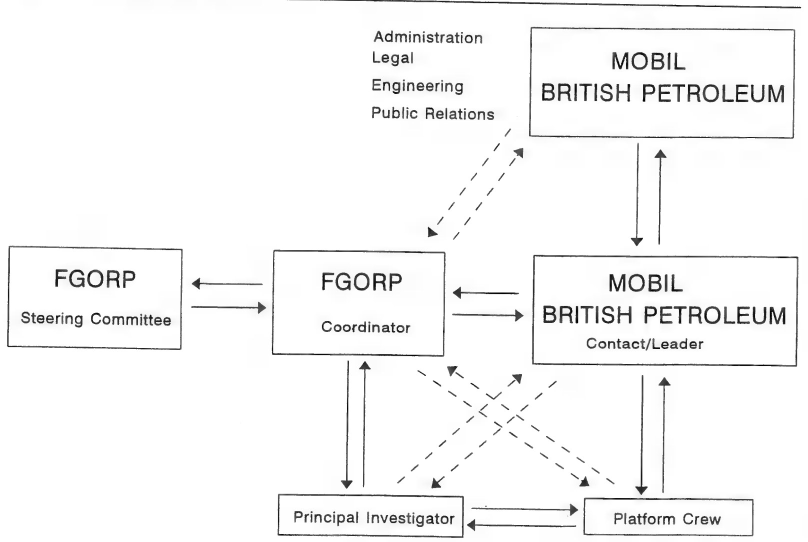
Wiebe et al. (1987) discusses the need and rationale for data collection in a long-term time series format. A network in the Gulf of Mexico could produce a comprehensive database in a real-time format for extended periods. Recruitment, trophic relationships, animal behavior, seasonal migration of pelagic species, long-term global change, physical oceanography, surface water/atmospheric dynamics, the dynamics of intermixing water masses, reef dynamics, primary productivity, transport of nutrients, sediment, and contaminants, and effects of extreme events such as hurricanes are potential topics of investigation.

There is a need to recruit and train motivated students in the fields of marine science. The "Man in the Sea" program of the 1970s was intended to encourage students to focus their attention on the oceans by providing a diversity of field experiences including exposure to offshore production platforms. State-of-the-art training programs and facilities are an essential requirement for recruiting and training marine scientists to integrate research safely and effectively and to apply marine research technology.

Platforms could be utilized as sites to instruct students and scientists in the ever-changing research technologies, such as the use of remotely operated vehicles, manned submersibles, advanced scuba technology, surface supplied diving, hyperbaric chamber operations, and underwater survey techniques. Somers (1993) discussed the need for and application of advanced diving technologies for scientific research. Training programs meeting certification requirements of diving program guidelines of state and federal agencies, the American Academy of Underwater Science, and academic research institutions could be conducted in a relatively safe and cost-effective training environment.

Real-time monitoring and reporting of sea and weather conditions through automated monitoring equipment mounted on platforms could be made accessible through public phone linkages. Not only would this provide a public service for the boating community, but also it would create a direct linkage between science in the Gulf and the general public.

FIGURE 1. Schematic representation of the communication and management structure of the Flower Garden Ocean Research Project (FGORP). Solid lines are primary lines of communication. Dotted lines are secondary lines of communication.



FGORP'S ORGANIZATIONAL STRUCTURE AND OPERATIONS

Members of the FGORP steering committee represent a diversity of interest and expertise with representatives of Mobil Exploration and Producing Inc., British Petroleum Inc., Corpus Christi State University, University of Texas Marine Science Institute, Texas A&M University, Minerals Management Service, National Oceanic and Atmospheric Administration (NOAA) National Marine Sanctuary Program, Texas A&M Sea Grant College Program, Environmental Protection Agency, Texas State Aquarium, and Louisiana Universities Marine Research Consortium. The committee provides oversight and guidance on current activities and advances the concept of oil and gas platforms as offshore research stations.

To streamline communications and minimize the number of persons required to implement a research project expeditiously, an FGORP coordinator and a MEPUS and BP contact/lead person were designated (Figure 1). Typically, a proposed research project is submitted to the FGORP coordinator who reviews it for any potential conflicts with other projects in progress. The proposal is then forwarded to the MEPUS or BP contact to start in-house consideration to determine if the proposed project could compromise the structural integrity of the platform, create a safety hazard, or disrupt the daily production activities of the platform. It is assumed that critical scientific review of the proposed research occurs during the funding solicitation phase.

If the proposed research is to occur within the boundaries of the Flower Garden Banks National Marine Sanctuary, the proposal is submitted to the sanctuary manager for approval. Once it is determined that the project can be conducted from the platform, the principal investigator is directed to the appropriate company operations and field personnel to implement the study.

A key element in the development of FGORP has been the need to minimize the legal liability of the private industry participants, in this case MEPUS and BP. Understandably, companies do not wish to assume increased liability by supporting personnel other than their own in a constantly changing environment that can be as challenging and hazardous as that of the outer continental shelf. In FGORP's case, legal counsel constructed an indemnity agreement to provide private sector participants protection from liability claims. This agreement must be signed by each agency or academic institution wishing to sponsor research utilizing a platform. In addition, each member of any given research team signs a liability release form before leaving shore.

Studies of larval recruitment, artificial reef productivity, audio/video survey technology, coral reproduction, and continuous real-time monitoring of sea level have been conducted off Mobil HI-A389A (latitude 27°54'30" N, longitude 93°35'6" W) (Figures 2 and 3). In addition, the platform has been used to train field technicians to complete underwater visual surveys using scuba technology.

To date, FGORP projects have utilized existing platforms. Research applications were not considered during design or construction of these platforms. Subsequently, research activities are limited to studies for which the platform can be safely retrofit to accommodate scientific equipment. With the support of the platform owners, marine scientists and platform design engineers could collaborate to add mounting brackets, deployment booms, and other physical structures to support research instruments and equipment to platforms as they are constructed. This would be particularly advantageous and productive when applied to platforms designed for the deeper waters of the continental shelf and slope.

A FULL-TIME PLATFORM RESEARCH AND TRAINING CENTER

Mobil platform HI-A389A is located within the boundaries of the Flower Garden Banks National Marine Sanctuary approximately 161 km south of Cameron, Louisiana, 185 km east of Freeport, Texas, and 1.5 km east of the coral reef cap of the East Flower Garden Bank. HI-A389A is predicted to reach the end of its production life around 1995. By federal law, the platform must be removed within one year. An alternative to removal would be to convert

FIGURE 2. Mobil HI-A389A as configured for the production of natural gas.

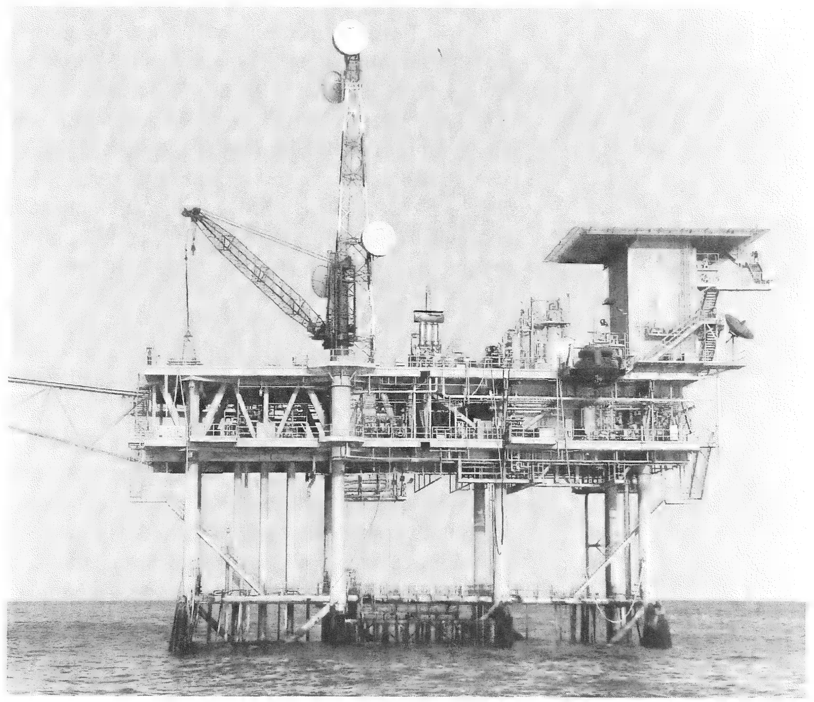
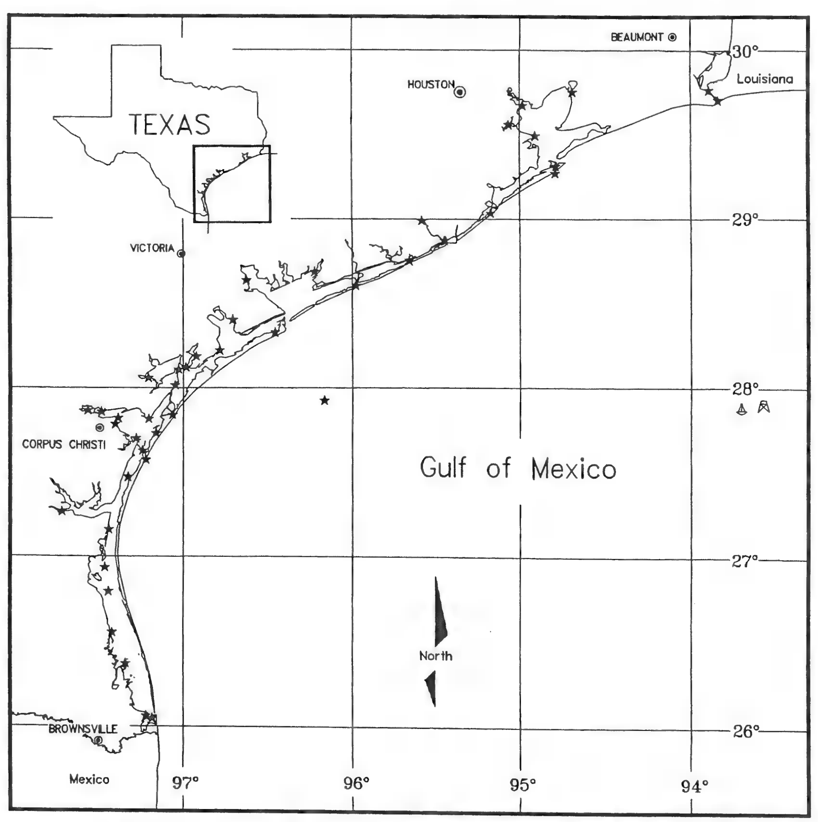


FIGURE 3. Map of northwest quadrant of the Gulf of Mexico.



LEGEND: SCALE 1" = 48 Nautical Miles
* TCOON Monitoring Stations
Mobil HI-A389A
Flower Garden Banks

Mobil HIA389A to a full-time research and training station.

Based on a return of 47 survey forms from scientists on the Texas Sea Grant Program "Request for Proposal" mailing list, there appears to be substantial interest in establishing an offshore research station in order to have year-round access to the outer continental shelf. On a scale of 1 to 10, with 10 being the highest score in support of creating an offshore station, the mean score was 8.2. The range of scores was 1 to 10 with 81 percent of the scores being ≥ 7.

Mobil HI-A389A is particularly suited to research and training activities. It is located in a water depth of 125 m, and the nearby reefs of the Flower Garden Banks, which crest at 17 m below the sea surface, make possible a diversity of training scenarios in real-life field conditions. The surrounding water is tropical with seasonal surface temperatures ranging from 19° C to 30° C and in-water visibility ranging from 20 to 60 m. Currents and sea states vary, and the flora and fauna is predominately Caribbean, with seasonal occurrence of pelagic oceanic species. Rezak et al. (1985) discuss numerous natural banks in the vicinity of HI-A389A, and Gallaway and Lewbel (1982) describe three faunal assemblages associated with production platforms in the northwest Gulf of Mexico extending from the shoreline "coastal zone" to the "blue-water zone" of the outer continental shelf.

HI-A389A is equipped with full-time living quarters for eight people, a reverse osmosis freshwater system, natural gas powered electrical generators, a 14 metric ton crane, and a helicopter landing pad. There are two habitable decks 20 m or more above the sea surface and working decks at 4 and 5 m above water surface. After removal of the gas production equipment approximately 6,500 m^2 of space would be available for expanded living quarters, wet/dry laboratory space, and the installation of research and training equipment. Safety equipment such as recompression chambers could be installed and be available for emergency treatment.

Because of its proximity to the East Flower Garden Bank, Mobil HI-A389A could be used as a field station from which to monitor and manage this unique resource. In 1992 an estimated 10,000 recreational dives were made on the Flower Garden Banks (S. Gittings, personal communication). With the increased public awareness of the Flower Garden Banks, the number of visitors to this marine sanctuary is growing as evidenced by the rise in the number of recreational charter boats in 1993 offering regularly scheduled trips throughout the year. It will eventually be necessary to provide on-site management for visitor safety and enforcement of visitation requirements.

The proximity of the Flower Garden Banks coral reefs and numerous other natural banks of the northwest Gulf of Mexico, as well as the growing number of artificial reefs in the area, create unique opportunities to study the ecological dynamics of reefs and productivity in varying water masses (e.g., temperate versus tropical).

Public relations, awareness, and education are important functions that could be carried out through the application of a full-time offshore research station. Such a station could be used to develop and disseminate innovative education and public awareness programs that would serve to foster a sense of stewardship for the Gulf of Mexico and a stronger bond between the public and research community. This opportunity could also be used to encourage greater corporate support of research efforts in the Gulf.

CHALLENGES TO BE MET

Precedent, liability, and financing are three primary challenges to converting HI-A389A to a full-time research station. MEPUS has expressed guarded interest in donating HI-A389A for conversion to a research station, stressing that once it ceases production of natural gas it will be necessary to divest MEPUS of any financial or legal liability associated with its continued presence and operation. This could be achieved by donating the platform to the Texas Parks and Wildlife Department (TPWD) Artificial Reef Program which was created through the Texas Artificial Reef Act of 1989. As provided for in the Act, liability and responsibility would be transferred to the TPWD Artificial Reef Program.

This donation would set a precedent for the TPWD and all federal agencies with oversight and permit responsibilities regarding the placement of structures in navigable marine waters. Specifically, Mobil HI-A389A would be a nonproducing natural gas platform left in a vertical position and operational as a research station. Under the Texas Artificial Program, it has been standard procedure to topple obsolete platforms, maintaining a minimum of 24 m of clearance. Toppling is not a requirement of the Texas Artificial Reef Fishery Management Plan (1990) but rather a concession to minimizing navigational hazards and liability and costs associated with maintenance.

Platforms rising to or above the water surface do constitute a navigational hazard. However, this is a navigational challenge that has been readily accepted and successfully managed as evidenced by the approximately 3,800 platforms currently in operation in the northern Gulf of Mexico.

Preliminary estimates of costs for operating an offshore research and training station are $300,000 to $400,000 annually. These costs include full-time staffing and research and training expenses, but not transportation. It is unlikely that any one agency or institution would be willing to assume the full cost of operating this facility. However, if an endowment fund could be established that would generate enough income to cover a significant portion of the operational costs, it becomes more feasible to draw adequate funding from a consortium of users to cover the balance of the operational cost.

The Texas Artificial Reef Program selectively accepts obsolete platforms for inclusion in the artificial reef program. The owner of the platform donates fifty percent of the money saved by not having to remove the structure to the Artificial Reef Program. Through this arrangement the Artificial Reef Program is endowed, the platform owner realizes significant savings, and recreational and commercial fishing opportunities are enhanced.

An endowment fund could be established with funds that would otherwise be used to remove HI-A389A. Investment revenues from this endowment would be used for maintenance and operational costs of the research and training station. Fees could be assessed to cover the balance of the operational costs not fulfilled by investment revenues. At that point in time when its function as a research and training station is no longer desired or justified, the endowment could be used to fund the cost of removal.

Management of the Mobil HI-A389A research station should be retained by the Texas Parks and Wildlife Department. Or it could be contracted to a research institution and/or a research program or consortium such as FGORP.

SUMMARY

In theory, conversion of an offshore oil or gas production platform would provide a stable foundation from which to conduct research including real-time, long-term data collection in all weather conditions as well as hands-on in-water research. Such a station could be used to encourage students to establish careers in marine science and to train students and scientists in advanced research technologies. It could support public service programs such as providing continuous information via automated telephone systems, providing sea state and offshore weather information, and establishing a real-time linkage between scientists and the general public.

At first glance, there appears to be adequate legislative and legal statutes and a potential funding mechanism to make this possible. However, these topics and a more definitive description of need will have to be developed through a detailed feasibility study.

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REFERENCES

Bright, T. 1993. Personal communication. Texas Sea Grant College Program. Bryan, Tx.

Busch, W.S. 1993. Government-industry alliance: New strategy for environmental research. *Mar. Technol. Soc.* J. 27(2).

Culliton, T.J., Warren, M.A., Goodspeed, T.R., Remer, D.G., Blackwell, C.M. and McDonough, J.J. III. 1990. Fifty years of population change along the Nation's coasts, 1960–2010: A special earth week report. NOAA, Office of Oceanography and Marine Assessment. Rockville, Md. 41 pp.

DSO Workshop, 1990. Deep Sea Observatories: Near-term opportunities and long-range goals. Report of a Workshop, November 7–9, 1989. Sponsored by Scripps Institution of Oceanography and Woods Hole Oceanographic Institution. Woods Hole, Mass. 54 pp.

Gallaway, B.J. and Lewbel, G.S. 1982. The ecology of petroleum platforms in the northwestern Gulf of Mexico: A community profile. U.S. Fish and Wildlife Service, Office of Biological Services, Washington, D.C. FWS/OBS-82-27. Bureau of Land Management, Gulf of Mexico OCS Regional Office, OpenFile Report 82–03. xiv + 92 pp.

Gittings, S. 1993. Personal communication. Flower Garden Banks National Marine Sanctuary. Bryan, Tx.

Lewis, J. 1993. Challenges and advantages of collecting upper air data over the Gulf of Mexico. *Mar. Technol. Soc. J.* 27(2).

National Research Council. 1992. *Oceanography in the Next Decade: Building New Partnerships.* National Academy Press. Washington, D.C. 202 pp.

Rezak, R., Bright, T.J. and McGrail, D.W. 1985. Reefs and Banks of the Northwestern Gulf of Mexico: Their Geological, Biological, and Physical Dynamics. John Wiley and Sons, New York. xviii + 259 pp.

RMRP. 1993. Gulf of Mexico Marine Research Plan 1992–1996. Gulf of Mexico Regional Marine Research Program, May 1993. Texas A&M University Corpus Christi. Center for Coastal Studies. Corpus Christi, Tx. 261 pp.

Somers, L. H. 1993. Mixed gases in scientific diving. In: Mixed Gas Diving: The Ultimate Challenge of

Technical Diving. T. Mount and B. Gilliam. Watersport Publishing Inc., San Diego, Calif. 392 pp.
Texas Artificial Reef Fishery Management Plan: Source Document. 1990. Fishery Management Plan Series Number 3. Texas Parks and Wildlife Department. Austin, Tx. 96 pp + Appendices.
Texas Artificial Reef Fishery Management Plan: Executive Summary. 1990. Fishery Management Plan Series Number 3. Texas Parks and Wildlife Department. Austin, Tx. 24 pp.
Wiebe, P.H., C. B. Miller, J.A. McGowan, and R.A. Knox. 1987. Long time series study of oceanic ecosystems. *Eos*, 68(44):1178–1190.

PAPER

The Texas Coastal Ocean Observation Network and Oil Platforms in the Gulf of Mexico

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ABSTRACT

The Texas Coastal Ocean Observation Network (TCOON) comprises a network of data collection platforms situated mainly in the bays neighboring the Gulf of Mexico. These platforms collect water level and other environmental and meteorological data for hazard management and environmental management of the Gulf Coast region. Data collected from offshore platforms in the Gulf of Mexico will be important to augment the TCOON data and to further our understanding of the hydrodynamic and meteorological processes affecting the environment in this region. Applications of this data are described.

INTRODUCTION

In 1989, the Conrad Blucher Institute for Surveying and Science (CBI) commenced the installation of three remote reading water-level gauges in the Corpus Christi region. These data collection platforms were installed primarily to aid the City of Corpus Christi in the management of hurricane emergencies. Since that time, CBI has worked with Lamar University at Beaumont, the Texas General Land Office, the Texas Water Development Board, and the National Atmospheric and Oceanic Administration's National Ocean Service to expand the network significantly in extent and function to become what is now generally referred to as the Texas Coastal Ocean Observation Network (TCOON). The data collected by the platforms are available for environmental management and hazard management along the Texas Gulf Coast. This paper briefly describes the network and selected applications currently using the TCOON data. These applications include the determination of littoral boundaries, monitoring of the wetland environment, and management of oil spills. Preliminary results from initial inspection of the data are presented showing the nature of the changes in water levels in the Corpus Christi region and also the importance of the relationship between the hydrodynamic processes occurring in the Gulf of Mexico and the bays and lagunas.

DESCRIPTION OF TCOON

The TCOON has previously been described by Jeffress (1991) and Garrett and Jeffress (1992; 1993) and presently consists of 41 data collection platforms situated in the bays, estuaries, and offshore along the Gulf of Mexico (Figure 1). Five of these platforms were established by the National Ocean Service and are part of the National Ocean Service National Water-Level Observation Network. The primary instrumentation on each platform is a next-generation water-level measurement system (Mero and Stoney, 1988). However, the equipment used to log data permits additional sensors to be included on each platform. Hence, some data collection platforms also collect data on wind speed, wind direction, water temperature, barometric pressure, pH, dissolved oxygen, and conductivity. The status of platforms is continually monitored and upgraded as additional data are required by the various sponsors of the network.

The environmental data collected at each platform are transmitted to CBI via one of three communication channels as depicted in Figure 2. Most of the platforms transmit data to CBI via the Geostationary Operational Environmental Satellite (GOES) to the National Environmental Satellite Data and Information Service (NESDIS) situated at Wallops Island,

FIGURE 1. The Texas Coastal Ocean Observation Network (TCOON). ★ denote TCOON stations.

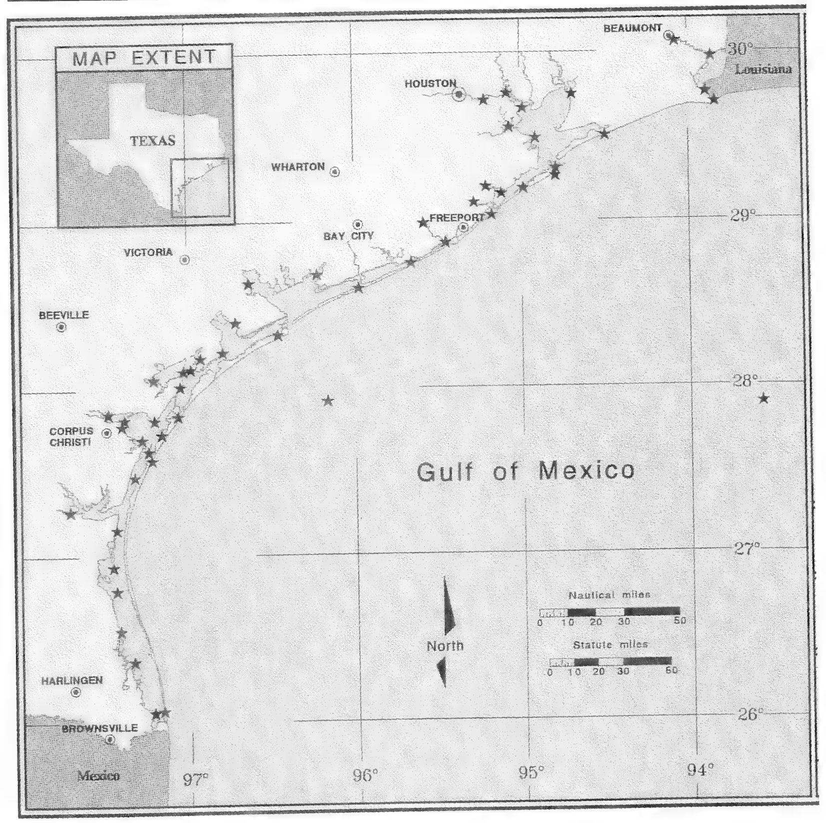
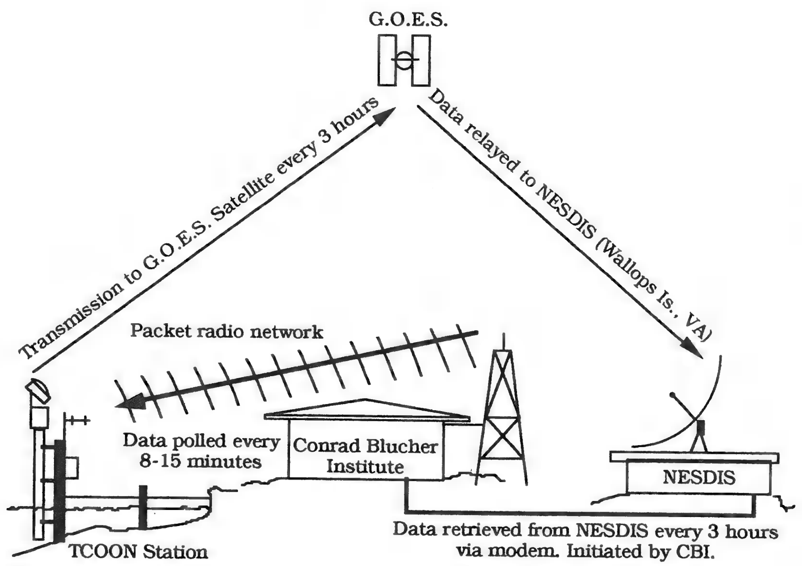


FIGURE 2. Communication paths for the TCOON.



Virginia. The CBI TCOON automatically downloads the data from NESDIS six times daily via telephone. Many of the gauges also transmit data directly to CBI via telephone or packet radio, so that some data can be obtained within a few minutes of being logged at the data collection platform. These near real-time capabilities are essential for hazard management applications such as hurricane emergency preparedness and response to oil spills.

The TCOON observation database has been developed on the INGRES® (INGRES Corporation, Alameda, California) relational database management system running on a Hewlett Packard 9000 720 RISC workstation. The relational database permits flexible access to the observational data. An additional benefit is that INGRES can be directly accessed from the ARC/INFO® (Environmental Systems Research Institute, Redlands, California) and GENAMAP® (Genasys, Fort Collins, Colorado) Geographical Information System (GIS) packages that CBI currently has running on the same computer system. This interaction permits other environmental databases to be directly integrated with TCOON data for further analysis and decision making. Additional software has also been written at CBI to access the database using the S-Plus® (Statistical Sciences, Inc., Seattle, Washington) statistical package that permits scientific analysis and graphical presentation of the data to be conveniently undertaken. This hardware and software system also permits ready access to the data and easy development and integration of databases for other environmental management applications.

APPLICATIONS

The TCOON system can in principle be used for any nearshore or estuarine environmental monitoring requirement. CBI's initial involvement was to provide water-level data to the City of Corpus Christi during hurricane emergencies. However, as the network has become operational and has been expanded with more gauges and more functionality, the data are being used for many other applications.

Oil Spill Response

One major application being developed for the TCOON aims to incorporate wind speed, wind direction, water temperature, air temperature, and other environmental data into a real-time graphical display for a potential oil spill site (Garrett and Jeffress, 1992; 1993). A prototype system is currently being implemented using data from five gauges that automatically transmit data to the CBI database every 8 to 15 minutes. The data will eventually be transmitted via Internet to the Texas General Land Office Oil Spill Prevention and Response Unit situated in Austin, Texas, where they can be used to manage and coordinate response to oil spill using GIS and oil-spill trajectory modeling software. Ideally, these data will also be integrated with other environmental "sensitivity" databases as part of a comprehensive coastal management process. The use of GIS technology will be central to this data integration process. When there is an oil spill, the database will enable location of appropriate cleanup equipment and personnel, identification of natural resources of the site, location of endangered man-made and natural features, and prediction of the trajectory of the oil spill. These functions will obviously be closely linked to other programs for the management of the environment in this region.

An example display screen from the prototype graphical interface developed with the Arc Macro Language of ARC/INFO is shown in Figure 3. The display indicates the location of the data collection platforms on a map of Texas and the Gulf of Mexico. Plots of the most recent water levels, wind speed and direction, atmospheric temperature, and atmospheric pressure can be obtained by pointing and clicking with the mouse on the symbol for any platform. Further analysis of the data or integration with other environmental datasets is relatively simple, as it resides in the underlying relational database. The first implementation of the prototype system will allow the Texas General Land Office staff in Austin to view meteorological and water-level data within minutes of being logged in the TCOON system. Eventually, this system will be expanded to add more data collection platforms, including those on offshore platforms, in order to give a more complete picture of the environment when an oil spill occurs.

Tidal Datum Definition

The shallow wetlands in the Corpus Christi area and other Texas bays and lagoons require accurate definition of water-level datums to enable littoral boundaries between submerged lands and privately owned lands to be determined. Because of the gentle slopes of the wetlands, changes in water level of a few centimeters can change the horizontal position of a littoral boundary by many meters, leaving many hectares of land with poorly defined boundaries. Accurate water levels are therefore required to establish the location of these boundaries.

Changes in water level in the bays are related to extremely complex forcing processes. Water levels of the Laguna Madre area near Corpus Christi are driven by long-term trends in the Gulf of Mexico and by local meteorological conditions, rather than astronomical tides alone. In addition, the astronomical tide in the area has relatively small range (less than 60 cm) and exhibits both diurnal and semidiurnal components. Littoral boundary definition is therefore not as simple as would be the case in a normal tidal regime.

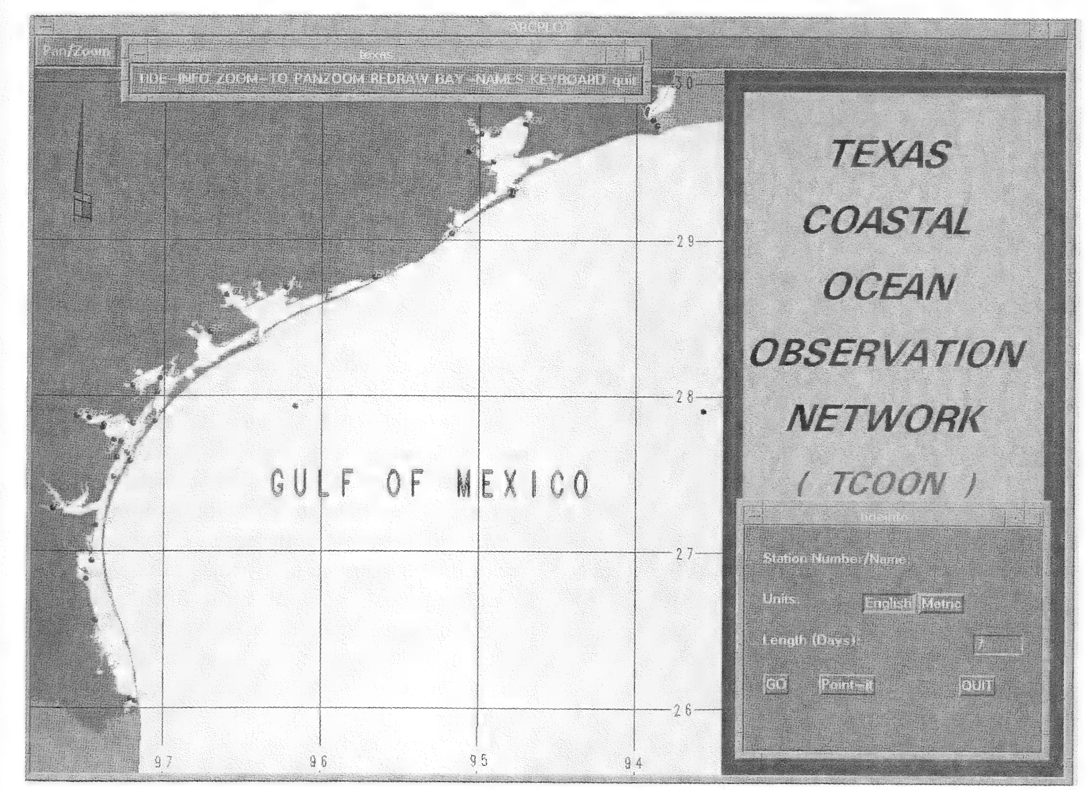
The National Ocean Service has long established the procedures needed to compute tidal datums. Many of these procedures are manually intensive and are difficult to apply to the Texas Coast. CBI is working with the National Ocean Service both to improve these procedures' applicability to the Texas coast and to reduce the need for manual processing. CBI is developing software to enable the automatic determination of tidal datums using water-level data from the TCOON system. Methods are also being developed to automate the surveying procedures to locate tidal datums on the ground using precise bar-code reading automatic electronic levels.

Environmental Management

Wetland areas are now increasingly recognized as valuable ecosystems because of their critical role as fish and wildlife habitats and as areas of water management and conservation (Tiner, 1984; Mitsch and Gosselink, 1986; Barrera et al., 1992). The bays and estuaries neighboring the Gulf of Mexico contain many wetland areas and are attracting increased attention for monitoring the impact of human and natural occurrences.

Two gauges in the network were added to supply primary water-level data for the Environmental Protection Agency (EPA) Galveston Bay National Estuary Program. The Corpus Christi Bay area has also recently been

FIGURE 3. Display of ARC/INFO menu interface for TCOON.



designated as an estuary of national significance by the EPA and has become part of the National Estuary Program. Any management plan for these regions will require information on the functioning of the natural system and the capability to monitor the effects of present and future human uses. Understanding the oceanographic processes that affect the region will also be of great importance, since they impact the habitat in the wetland regions. Monitoring the relationship between water level and other environmental conditions between the Gulf of Mexico and the bays will be important to the future of this area. The CBI databases will enable scientists to better understand the coastal processes and form an important resource for the understanding and future management of the coastal environment for this region.

PRELIMINARY ANALYSIS OF WATER-LEVEL DATA

Offshore platforms add to any hurricane preparedness activities as well as provide water level and meteorological data for oceanographic and scientific investigation. To this end, CBI has installed data collection platforms on offshore oil and gas platforms in the Gulf of Mexico. These two platforms measure and transmit water level, air and water temperature, wind speed and direction, and barometric pressure data. Offshore gauges are important for modeling the hydrodynamic processes in the bays neighboring the Gulf of Mexico (Figure 4).

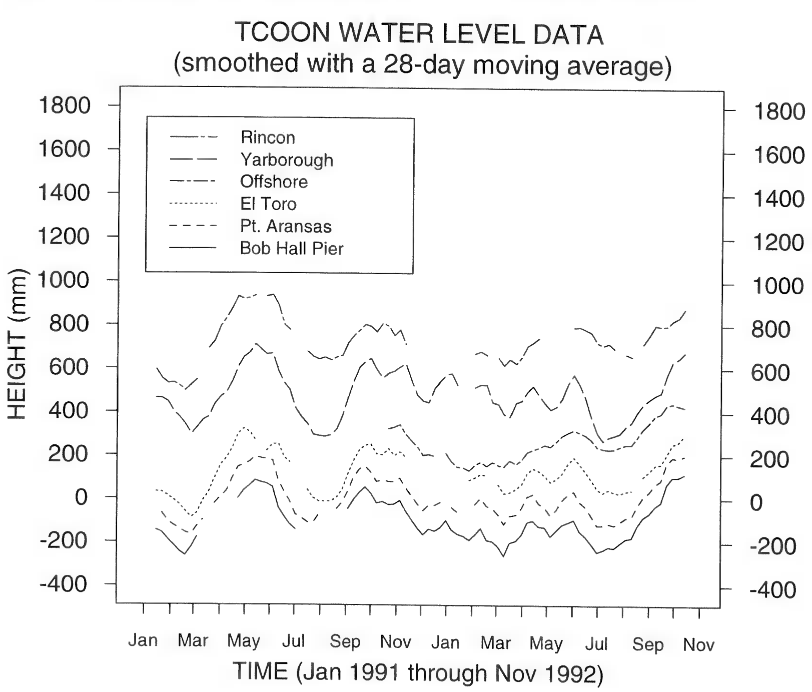
Figure 4 shows the water levels for January 1991 to October 1992 for the gauges Offshore, Bob Hall Pier, Port Aransas, Yarborough, El Toro, and Rincon. The Offshore gauge is located on a Corpus Christi Oil and Gas, Inc., platform situated approximately 70 km east of Corpus Christi, Texas. Bob Hall Pier is located on the Gulf Coast near Corpus Christi. Port Aransas is located on the Port Aransas channel, which is the main access channel to Corpus Christi Bay. Yarborough, El Toro, and Rincon are situated in the Laguna Madre to the south of Corpus Christi. A 28-day moving average filter has been applied to these data to remove the short-term effects of tides and winds. All series are noticeably correlated with a near one-to-one correspondence between changes in water level in the Gulf, Corpus Christi Bay, and the Laguna Madre. The water-level range can be up to half a meter over periods of up to 100 days.

Table 1 shows the power of these long-period signals as a percentage of the total variance of the water levels at each of these gauges. The root-mean-square (RMS), minimum, and maximum of the smoothed water-level data are also shown.

An important factor here is that the water levels at the three Laguna Madre gauges are dominated by the long-period signals with over 50 percent of the water-level variance being contributed by these long-term constituents, whereas at Port Aransas, Bob Hall Pier, and Offshore the astronomical tide signal is more dominant. The correlation between all gauges, shown in Figure 4, indicates the importance of the general hydrodynamic conditions in the Gulf of Mexico to water level in the Corpus Christi region. Long-term trends in the Gulf of Mexico are directly transferred and may be amplified in the bays and lagunas.

Currents and water level in the bays near Corpus Christi cannot be treated separately from what is happening in the Gulf of Mexico. Water level, meteorological and other environmental data, collected from offshore platforms, will be needed to fully understand and model these processes. Determining the relationships between the Gulf of Mexico and the bays will be important for future understanding of the marine environment of the region. Collecting environmental data at platforms in the Gulf of Mexico is therefore important to further our understanding of coastal processes of this region and will also be important for any hazard management and environmental management programs.

FIGURE 4. TCOON water levels smoothed with a 28-day two-sided moving average for Offshore, Bob Hall Pier, Port Aransas, Yarborough, El Toro, and Rincon platforms.



THE FUTURE

The TCOON is a relatively recent development and is, therefore, still evolving. However, the development of the data-collection and database procedures is stable so that data and information can be easily provided for any platform. Data collection has now been undertaken for a long enough period to begin reliable water-level analysis for the region and to continue development of our understanding of the coastal processes of the region.

The network is currently providing data to assist needs for hurricane preparedness, littoral boundary definition, water-quality assessment, real-time water-level and meteorological monitoring, marine safety, and recreational use of the bays and estuaries of South Texas. Applications are being developed to improve our ability to monitor and manage oil spills in the region. The data will also be a valuable resource for the future monitoring of long-term sea-level changes and shoreline subsidence in the region. All of these applications will be aided by the provision of similar data from offshore platforms.

ACKNOWLEDGMENTS

The authors would like to thank the Texas General Land Office, the Texas Water Development Board, the National Ocean Service, and the Environmental Protection Agency for their support of the TCOON. Lamar University contributes to the operation of the network. Support for the oil spill response development is provided by Texas General Land Office contract No. 92-170R.

TABLE 1. Statistics of water levels smoothed with a 28-day two-sided moving average.

Station	Power of Long Period Signal (% of Variance)	RMS (mm)	Minimum Level (mm)	Maximum Level (mm)
Offshore	19	82	−129	183
Bob Hall	22	100	−167	228
Port Aransas	36	97	−174	212
Yarborough	69	113	−210	233
El Toro	73	99	−210	209
Rincon	53	107	−229	226

REFERENCES

Barrera, T.A., Waechter, D.A., Jeffress, G.A. and Tunnell, J.W. Jr. 1992. Mapping wetland vegetational changes and plotting ecological data in Oso Bay. In: *Proceedings of Urban and Regional Information Systems Association Conference.* Vol. I. 251–260. Washington, DC: Urban and Regional Systems.

Garrett, M. and Jeffress, G.A. 1992. Incorporation of real-time environmental data into a GIS for oil spill management and control. In: *Proceedings of GIS/LIS'92, American Congress on Surveying and Mapping,* 247–255. Bethesda, MD: American Congress.

Garrett, M. and Jeffress, G.A. January 1993. Managing Oil Spills. *Geo Info Systems,* 29–35.

Jeffress, G. A. 1991. Next generation water level measurement for the Texas coast. In: *Proceedings of The Second Australasian Hydrographic Symposium,* The Hydrographic Society, Australia, 407–415.

Mero, T.N. and Stoney, W.M. 1988. A description of the National Ocean Service next generation water level measurement system. In: *Proceedings of the Third Biennial NOS International Hydrographic Conference,* Baltimore, Maryland, April.

Mitsch, W.J. and Gosselink, J.G. 1986. Wetlands. New York: Von Nostrand Reinhold. 539 pp.

Tiner, R.W. 1984. *Wetlands in the United States: Current Status and Recent Trends.* USFWS National Wetlands Inventory. Washington, D.C., 59 pp.

PAPER

Challenges and Advantages of Collecting Upper-Air Data over the Gulf of Mexico

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ABSTRACT

The National Severe Storms Laboratory (NSSL) has conducted two field experiments over and around the Gulf of Mexico since 1988. The scientific motivations for these experiments are briefly reviewed, and the suite of observational platforms used in the data collection are noted. Special attention is directed toward the collection of upper-air data from the Loran-C in the ocean environment during late winter to early spring. Data from this upper-air system are examined not only with the intention of identifying logistical difficulties in obtaining the data but also to highlight the quality of the data and their value in both basic meteorological research and operational weather forecasting. The primary results of the study are (1) reliable upper-air data can be obtained from ships and oil platforms using the Loran-tracked system; (2) these data have exceptional vertical resolution that reveal the evolution of the mixed layer of air adjoining the sea surface; and (3) these observations can influence and help improve operational severe storm predictions.

INTRODUCTION

It is generally accepted that the Gulf of Mexico is the primary source of water vapor for both general precipitation and severe storms in the central United States (Rasmusson, 1967); yet there have been relatively few investigations of the details of moisture transport from the Gulf, or the modification process that occurs when continental air plunges southward over this body of water. In the fall of 1986 scientists at the National Severe Storms Laboratory (NSSL) in Norman, Oklahoma, outlined a research program aimed at obtaining a better understanding of the role played by the Gulf of Mexico in our severe storm environment (see Lewis et al., 1989).

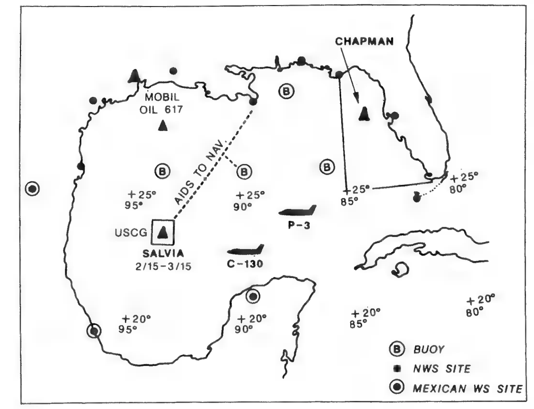
After outlining the research program, a field experiment was planned and carried out in February and March 1988. A subsequent experiment of more limited scope followed in March 1991. We concentrated on February and March (the winter/spring transitional season or cool season) because a broad spectrum of weather occurs along the Gulf Coast during these two months.

One of the major problems facing forecasters during this cool season is the forecast of ceiling, visibility, and fog at major aviation hubs, such as Houston and New Orleans, as well as the oil-rig platforms in the continental shelf area. Deteriorating weather conditions can change from visual flight rules (VFR) to instrument flight rules (IFR) within 30 min. Conditions are generally associated with return of a shallow moist layer capped by a strong inversion. In other situations, the moist layer is deeper and tropical in nature and can lead to deep convection. Some of the most notable storm outbreaks in the central United States have occurred during this cool season (e.g., April 3, 1974, tornado outbreak; February 27, 1971, Mississippi delta outbreak; and March 28, 1984, Carolinas outbreak).

Upper-air measurements in the lowest 1 to 2 km (boundary layer) are critical to accurate forecasting in these cool season events. Indeed, atmospheric structure through the entire troposphere (~10 km) is important, but the boundary layer near the air/ocean interface typically contains the bulk of the water vapor in the atmospheric column. At the present time, the U.S. and Mexican weather services operate a total of 11 sites that ring the Gulf where upper-air observations are synchronously made twice a day. (Since 1990, the Mexican stations have been limited to one observation per day.) To augment these observations in our 1988 experiment, we established three upper-air sites over the Gulf: (1) on Mobil Oil platform 617 at the edge of the continental shelf off the Texas-Louisiana coast, (2) on U.S. Coast Guard (USCG) Ship *Salvia*, and (3) aboard the NOAA survey vessel Chapman. We also added an upper-air site at Galveston, Texas, to fill the gap between the National Weather Service (NWS) sites at Victoria, Texas, and Lake Charles, Louisiana. Thus, we had 15 sites for the 1988 experiment, and these were operated during a six-week period, mid-February through the first week in April. Figure 1 gives a plan view of these stations. All experimental sites took observations in concert with the U.S. and Mexican weather service sites during this six-week period. When key episodic events took place, observations from all 15 locations were collected at 6-hour intervals instead of the usual 12-hour interval. Nearly 800 upper-air observations were collected from this set of stations during the 1988 field program (see Lewis et al., 1989, for details).

In this paper, typical weather events over the Gulf of Mexico in the cool season will be briefly described. The upper-air observation network that has been employed to study these events is explained, with emphasis on collection of data in the marine environment. Finally, the paper ends with a commentary on the value of these data for basic research and operational forecasting.

FIGURE 1. Upper-air sites and NOAA buoy sites that were used in the 1988 experiment. Upper-air observations over the Gulf were obtained from two ships (*Salvia* and *Chapman*), the oil-rig platform (Mobil 617), two aircraft (NOAA's P-3 and the USAF's C-130), and the weather service sites in the United States and Mexico that ringed the Gulf. The CLASS upper-air system was used at those sites denoted by "▲'s".



METEOROLOGICAL EVENTS IN THE WINTER/SPRING COOL SEASON

Since weather events over and near the Gulf are profoundly influenced by the physiography of the region, a brief examination of the topography of the surrounding land masses and the bathymetry of the Gulf basin is warranted. Figure 2 succinctly highlights the features of importance. The continental features to be noted are (1) the coastal plain which is wide along the northern boundary but narrows along the western boundary, (2) the Yucatán peninsula which is flat and does not obstruct the low-level flow of air, and (3) the Sierra Madre Oriental Mountains that abruptly adjoin the coastal plain along the western boundary. The notable bathymetric features are (1) the continental shelf's marked variability with its width ranging from a mere 25-km width on the southern boundary (near Vera Cruz) to over 200 km off the coast of Texas and Louisiana, and (2) an abrupt continental slope exists where the associated bathymetry exhibits a "stair-step" structure with deep oceanic water adjacent to the shallow water over the shelf.

Figure 3 is a view of sea surface temperature (SST) in February 1988 and the long-term average or climatology for this same month. Notable in this figure are the strong gradients in the continental shelf areas and the protrusion of warm water north of the Yucatán Straits. This warm water is the Loop Current, a branch of the Gulf Stream that enters the Gulf through the narrow straits, executes a large anticyclonic (clockwise) trajectory, and then exits through the Florida Straits. With so much variability in the SST over the Gulf in the cool season, air mass modification over the Basin is also quite variable. This variability is one of the factors that contributes to the difficulty in making accurate forecasts.

FIGURE 2. Map of the floor of the Gulf of Mexico and topography over the neighboring land masses taken from *Atlas of the World*, National Geographic Society (Garrett, 1981). Elevations and depressions with respect to mean sea level are given in meters.

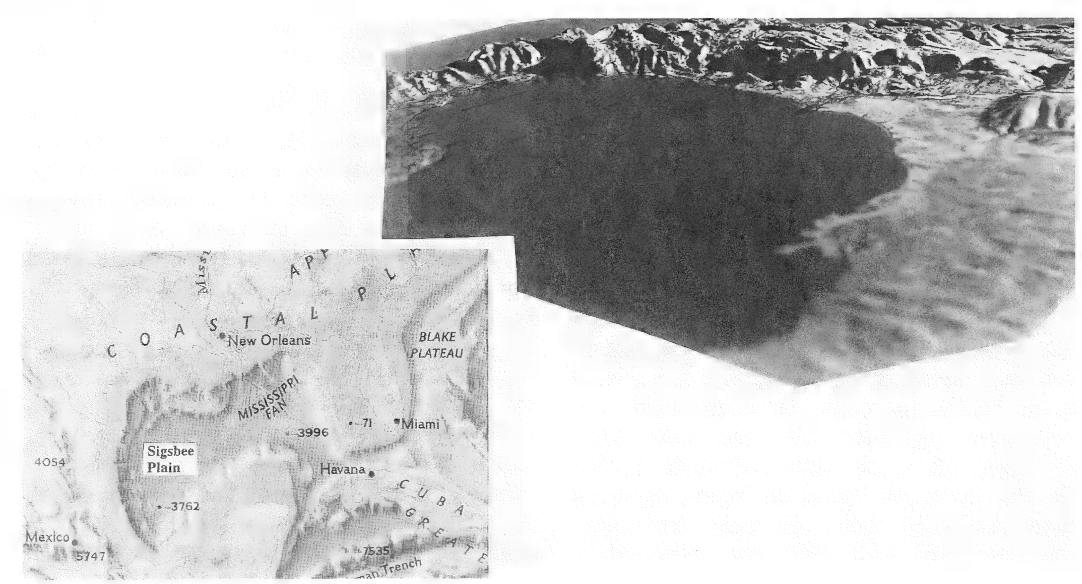
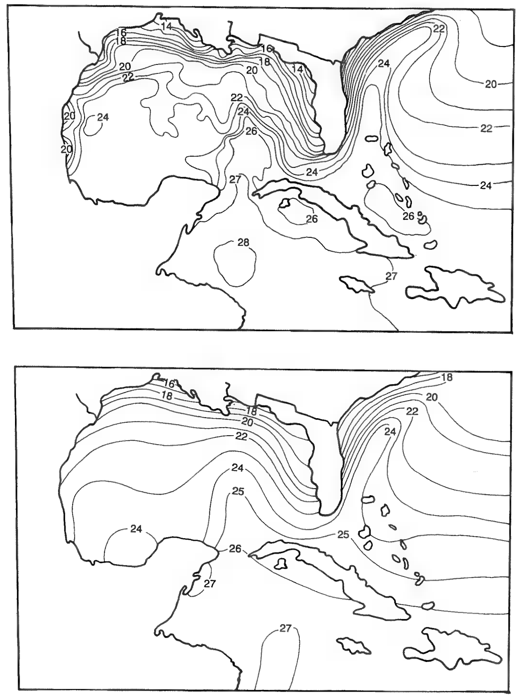


FIGURE 3. Sea-surface temperature (°C) over the Gulf of Mexico and Caribbean Sea in February. The top figure shows the distribution obtained from infrared data collected aboard the NOAA polar orbiting satellite during the week of February 21 to 27, 1988. The analysis was generated at NOAA/NESDIS, Madison, Wisconsin. The data for the bottom figure were obtained from the U.S. Navy Climatological Atlas (U. S. Navy, 1986) that used observations collected over a period of 30 years (1950-1980).



As will be shown, the air that tracks southward over the Gulf in February and March generally reverses its direction within a few days and returns to the continent. Consequently, those meteorological events that execute a complete cycle of cold air outflow from the continent and a subsequent reversal or inflow to the continent have been termed *return flows*. A concise summary of these weather events can be found in Crisp and Lewis (1992). Just as the bathymetry exerts an important influence on the SSTs, the topographic features surrounding the Gulf are germane to the trajectory of air involved in these return flows. This is usually evident by examination of imagery from weather satellites.

Although satellite imagery is essentially two-dimensional and does not resolve important vertical structure in the atmosphere, it serves as a valuable tool to examine the evolution of weather events qualitatively. Figure 4 shows a sequence of four visible images from the Geostationary Operational Environmental Satellite (GOES) taken on each of four consecutive days, March 13-16, 1988. By examining the cloud imagery, the larger-scale atmospheric motions can be inferred.

In the upper-left panel of Figure 4, which represents information on March 13, 1988, 1801 UTC (1201 CST), a cloud band straddles the central Gulf. These clouds are near the leading edge of cold/dry air that has moved from the continent to the sea. A front separates this cold/dry continental air from the tropical air south and east of the front. By March 14, the cold/dry air (which has been substantially modified by the underlying warm water) moves further southeast. In the western Gulf, the cold air spreads out and banks against the Sierra Madre Oriental range. As the air gradually moves up the mountains, it cools to the condensation point and thick stratocumulus clouds form. These clouds have tops around 3 to 4 km.

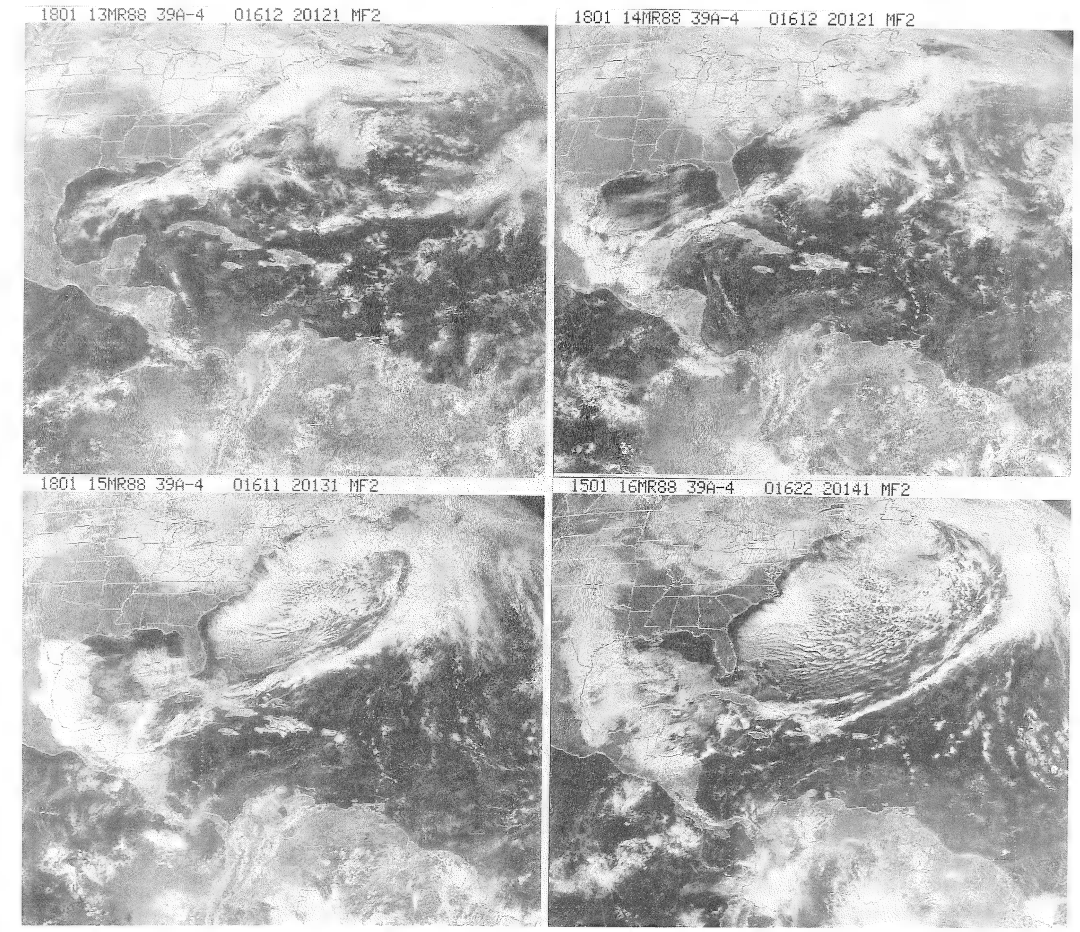
By the 15th, the frontal boundary has become nebulous because the contrast in temperature and moisture across this boundary has been considerably weakened by the modification process. In the western Gulf, the surface and low-level winds (<4 km) have shifted around and are directed toward the northwest. These changes in wind are reflecting the passage of the surface high-pressure region out of the Gulf and the emergence of a low-pressure system over the Great Plains. This rhythmic progression of large-scale (continental scale) pressure systems is typical of the cool-season weather over the Southern Plains. Thus, the second phase of the cycle commences, namely the return of modified air to the continent. By 1601 on March 16, the satellite imagery depicts the surge of modified air up into central Texas and western Oklahoma in advance of the low pressure system moving over the Rockies. This surge is manifested as a band of stratus clouds in the figure.

UPPER-AIR NETWORK OVER THE GULF

Suite of Observations

As shown in Figure 1, the network of upper-air observations used during the 1988 experiment provides good coverage over the Gulf—except for the southwestern region and the corridor between Yucatán and south Florida. The figure indicates that the *Salvia* covered the region south of buoys, but operational commitments kept her near 25°N. Upper-air data were also collected by NOAA's research aircraft, the P-3 Orion. Dropwindsondes, instrument packages parachuted from the plane and tracked by the OMEGA navigational system, provided the upper-air data from the aircraft (Smalley, 1978). A similar service was provided by U.S. Air Force C-130 aircraft that operated out of Keesler Air

FIGURE 4. Visible imagery from the NOAA geostationary satellite on four consecutive days. The times (UTC) for each photograph are given in the upper left hand corner of each panel where 1800 UTC is noon (CST).



Force Base, Mississippi. The C-130 could be requested to fly a track through the southwestern Gulf to fill that void, but since the weather observations were secondary to the primary mission of Air Force training, coordinated upper-air data in this region was often difficult to obtain. The NOAA aircraft was primarily used to study air/sea interaction over the warmest waters of the Gulf, in the area of warm intrusion associated with the Loop Current. Accordingly its range was also restricted.

Land-Based Upper-Air Observations

Brief mention is made of the upper-air observations at coastal locations operated by the weather services. This is done to distinguish them from the offshore observations discussed in the next section. The upper-air systems on land are called GMD's or ground meteorological devices, where the prefix AN/GMD is sometimes used to indicate Army-Navy (Sanders et al., 1978). These units have been the meteorologists' most dependable and valuable source of upper-air data since their development just prior to World War II. The National Weather Service (NWS) operates ~100 AN/GMD stations over the United States. They are called rawinsonde or RAOB stations because of the radio communication that is used in their operation. Instrument packages are attached to helium-filled balloons that rise at the rate of ~5 m s^{-1}. Instruments sense pressure, temperature, and humidity, and this information is radioed back to the ground receiver. A radiotheodolite is used to track the balloon and measures the direction of arrival and distance of the reflected radio wave, thereby providing two of the three coordinates required for a rawinsonde position estimate. Height estimates based on the pressure observation (in concert with the assumption of hydrostatic balance) provide the third positional coordinate, elevation. The relative plan positions (E/W, N/S) are used with the associated time increments and elevation to obtain a vertical profile of the horizontal wind. The vertical velocity of the air is generally much smaller than

the horizontal wind vector and cannot be obtained with this instrument.

Offshore Upper-Air Observations

For our upper-air observations at sea, we have used the CLASS (Cross-chain Loran Atmospheric Sounding System) developed at the National Center for Atmospheric Research (NCAR) (Beukers, 1978). Since positioning is determined by referencing the balloon location with respect to several distant transmitter sites (emitting low-frequency electromagnetic waves, LF), the radar tracking from the ground station (GMD) is obviated. Consequently, the system is ideal for use aboard ships and other mobile platforms. Loran-C is a navigation aid used primarily along the coasts of North America, Europe, and Asia for ship navigation (see Bowditch [1802] for a brief history). A rawinsonde system was developed ~25 years ago using Loran-C to measure winds, and an NCAR team continued to develop the system to meet the needs of the research community (Lauritsen et al., 1987).

The thermodynamic data (pressure, temperature, and water vapor) collected from the CLASS are comparable to those obtained from the land-based GMD systems. (Typical errors are $\pm 0.2°C$, ± 0.3 mb, and $\pm 2\%$ for temperature, pressure, and relative humidity, respectively.) The improved Loran positioning and the increased frequency of data transmission with the CLASS system, however, results in a much better vertical resolution of the data. The faster transmission rate results in the acquisition of data every 25 m in the vertical. The accuracy of positioning depends on the number and relative position of Loran transmitting sites, of course. There were seven Loran navigation transmitting stations that could be accessed (where a minimum of three are required for positioning). Figure 5 shows the location of the Loran transmitter stations typically involved in our tracking. Errors in the wind estimates are a function of the strength of signals (distance between instrument package and tracking stations) and the geometry of "triangulation." Wind errors are typically: ± 1 m s^{-1} in magnitude and (0-5) degrees in direction for moderate wind speeds of ~20 m s^{-1} (Rust and Marshall, 1989; Passi and Morel, 1987).

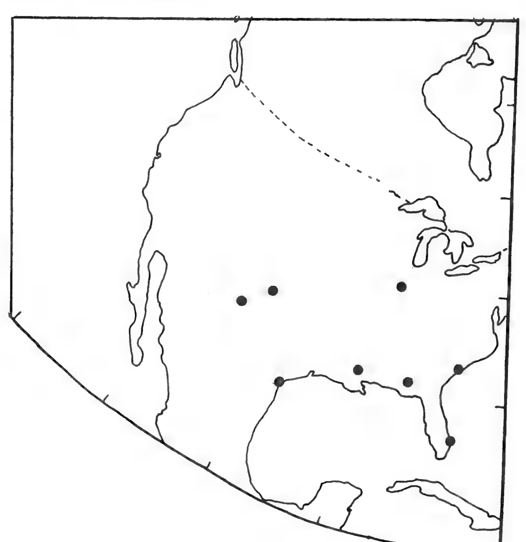
OPERATION OF CLASS ON MOBIL PLATFORM 617

Two of the offshore CLASS units were aboard ships, and one was on Mobil's oil-rig platform 617 (Figure 6), located at ~28°N, 93°W on the edge of the continental shelf. In this section, we will discuss the collection of upper-air data from the CLASS on 617 since it presented the most challenges. However, it should be clear from the ensuing discussion that several issues are pertinent to any platform at sea.

The equipment needed to operate CLASS includes (1) tanks of helium to inflate balloons (four 200-gram balloons per standard tank), (2) rawinsonde instrument packages (Vaisala RS 80), (3) 403 MHz receiving antenna, (4) prelaunch whip antenna (100 kHz), (5) personal computer (PC) (COMPAQ 386-20E) with monitor, printer, and associated software; and (6) CLASS hardware (~4 cu ft). To these, standard tools and electrical wiring should be added—also sheet metal for attaching antennas to the rig, launch cradle (for holding instrument package before lift-off), and a launch tube for controlling inflated balloons in high winds (Rust and Marshall, 1989).

Most of the problems that interfere with the mechanics of a successful launch are related to the limited number of launch positions available on the rig. Positioning is important for two primary reasons: (1) the low-level air properties should be minimally affected by the platform itself, i.e., the effects of the platform's sources and sinks of heat and moisture should be minimized, and (2) the line of flight of the balloon should have a minimum number of obstacles that could puncture the balloon or tangle the instrument package. The lowest levels of the platform (sea level) were unacceptable because of the pilings, metal cross-beams, and other support structure. The heliport (bull's-eye target in Figure 6) was also unacceptable because of heat sources near this landing and because of turbulence in high wind conditions that compromised personnel safety.

FIGURE 5. Location map for the Loran tracking stations that could be accessed by the balloons/instrument packages launched from Mobil 617.



Consequently all launches were made from the first and second decks above sea level (~20 m and 30 m, respectively). The two levels below the heliport had limited open space and were unacceptable as launch sites.

Aside from the mechanics of launch, the tracking of the sonde is affected by the relative positioning of the receiving antenna and the transmitter on the ascending balloon. If there is a mass of machinery or other obstructing material between the receiving antenna (on the platform) and the transmitting antenna (on the rising sonde), Loran tracking is momentarily lost. This tracking is not restored immediately, but typically takes several minutes. This time delay generally results in loss of data in the lowest kilometer above the sea surface (signal loss for 3 min translates into ~1 km of vertical displacement). To minimize this problem, the receiving antenna was fixed to a high point on the platform. A position atop one of the large cylindrical compressors was chosen where the antenna could be bolted to a piece of sheet metal. This location was slightly lower than the heliport.

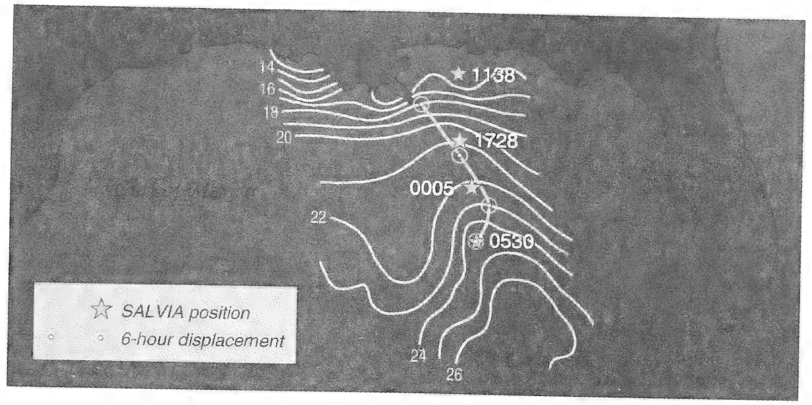
Launching in high wind conditions presented a host of problems. Typical winds in these return flow situations are 15 to 20 m s^{-1} (30 to 40 kts) with gusts to 25 m s^{-1}. Since the launches are generally made "down wind" of the platform, i.e., from that edge where the wind takes the balloon to sea instead of over the platform, there is considerable generation of turbulent eddies and vortex shedding on this downwind side of the platform. These vortical motions can cause the balloon and instrument package to execute erratic trajectories and occasionally the package ends up in the ocean. Once a package has been soaked with seawater, the electronics generally fail. The velcro-bound launch tube is an essential component to the launch in these high wind conditions. Control of the inflated balloon and instrument package is critical to the Loran-C tracking. For example, if the Loran-C receiving antenna ("rope type") attached between balloon and instrument package) starts to whip around in the strong winds on the platform and contacts the various metal fixtures or operators, the signal is generally lost. Figure 7 shows two operators preparing for a launch in calm conditions. Even in quiescent conditions the launch tube that surrounds the balloon helps the operators direct the balloon away from the metal fixtures and machinery in the vicinity of the launch site.

Despite the difficulties in obtaining upper-air data from the platform, our success rate was high. During the 1991 experiment, 75 launches were attempted, and 66 were successful. In most of the unsuccessful events, we were able to prepare and ground-check a new instrument package and get it airborne within 30 min of the scheduled launch time. The success rate for launches during the 1988 experiment on Mobil 617 were comparable to the 1991 experiment.

FIGURE 6. Photograph of Mobil Oil platform 617 in the West Cameron production area. The heliport is clearly identified by the concentric red/white circles on the top of the living quarters.

FIGURE 7. Operators prepare to release a balloon and instrument package on Mobil 617. The balloon is confined within a flexible cylindrical launch tube that is fastened by the velcro-strip running along the length of the tube.

FIGURE 8. The surface air trajectory (curved line connecting circles) and the position of *Salvia* when it launched CLASS. The sea-surface temperature (°C) is superimposed on these positions. The initial point of the trajectory (near the Mississippi flume) is valid at t=1200 UTC, February 21, 1988. Subsequent positions are at 6 h intervals.



BENEFITS OF UPPER-AIR OBSERVATIONS OVER THE GULF

Basic Research

During return flow events over the Gulf we are interested in knowing the rate at which the cold/dry air is modified by the warm water over which it travels. To measure this rate of change, we would ideally like to follow the air as it moves out over the Gulf and systematically launch the CLASS. (This is called "Lagrangian" tracking in accord with the concept of following parcels in classical fluid mechanics.) We were able to accomplish this type of tracking for one case in the 1988 experiment. It occurred between February 21 and 24, and the *Salvia* was able to keep pace with the cold/dry air outflow from the continent that moved toward the warm waters of the Loop current.

Figure 8 shows the position of *Salvia* as it travelled from its home base (Mobile Bay) to the northern edge of the Loop current. Using an unusually large set of surface reports from the ships of opportunity and the *Salvia*, the trajectory of surface air is shown on this same diagram. The CLASS soundings were taken from *Salvia* at the locations indicated by ★'s. The last three launches are nearly coincident with the surface air trajectory. The soundings were taken at ~6 h intervals.

The sounding of the low-level temperature and water vapor on February 22, 1988, 0530 UTC, is shown by the "x's" in Figure 9. The profiles indicate that the vapor content of the air is ~5.5 g kg^{-1} (5.5 parts per 1000 of the air sample) in the lowest 600 m. This uniformity is characteristic of what is called the "mixed layer" adjoining the sea surface. When the temperature is mixed in this same layer through the action of buoyant plumes (driven by the warm lower surface), it typically assumes an adiabatic profile where temperature decreases at the rate of ~10°C/km (dashed line in Figure 9). This "lapse-rate" extends to ~1,000 m at 0530 UTC. An ideal mixed layer would be characterized by an adiabatic layer with uniform vapor content extending to the same height, but these idealizations are rarely realized for a host of reasons that include condensation effects and varying entrainment into the turbulent plumes. When all CLASS soundings taken from *Salvia* are examined collectively, the rate of heating and moistening can be quantitatively determined (see Lewis and Crisp, 1992). For reference, it should be kept in mind that when the air came off land, it was characterized by a surface temperature of 10°C, vapor content of 3 g kg^{-1}, and a shallow inversion, i.e., the temperature next to the ground increased with height over a depth of ~50 m.

It is valuable to compare the structure of the air when it is over the Loop Current (x's in Figure 9) to its state when it returns to shore. Unfortunately, the *Salvia* was unable to track the air as it turned westward and northward (The ship could not keep pace with the rapidly accelerating air.) Some idea of change of state can be determined, however, by looking at the February 23, 1988, 1800 UTC sounding from Mobil 617.

The inset on Figure 9 shows the track of surface air as it moved clockwise from the continent to the Loop Current and then back toward land. The air that was sampled at Mobil 617 could be tracked back to the northern edge of the Loop Current two days earlier. The sounding data from Mobil 617 is plotted alongside the earlier data from *Salvia*. By comparing these graphs, it is clear that significant warming and moistening have taken place as the air moves from the Loop Current (*Salvia* data) back toward the edge of the continental shelf (617 data). Notice the abrupt discontinuity in vapor at ~1,800 m on the 617 sounding. This is the top of the 'mixed layer' discussed earlier and is denoted by the vertical arrow extending from the surface to 1,800 m. The temperature data corroborates this mixed layer height since the adiabatic profile extends to ~1,900 m, and the vertical arrow on the temperature graph is used to indicate this height. Keep in mind that this comparison of soundings gives only a rough idea of the modification process because we have not tracked the same air column. We are nevertheless confident of the general characteristics, i.e., a continual deepening of the mixed layer that gradually warms and moistens. These features of the modification process have been addressed by a series of articles in the recent special issue of the Journal of Applied Meteorology (August 1992).

Operational Forecasting

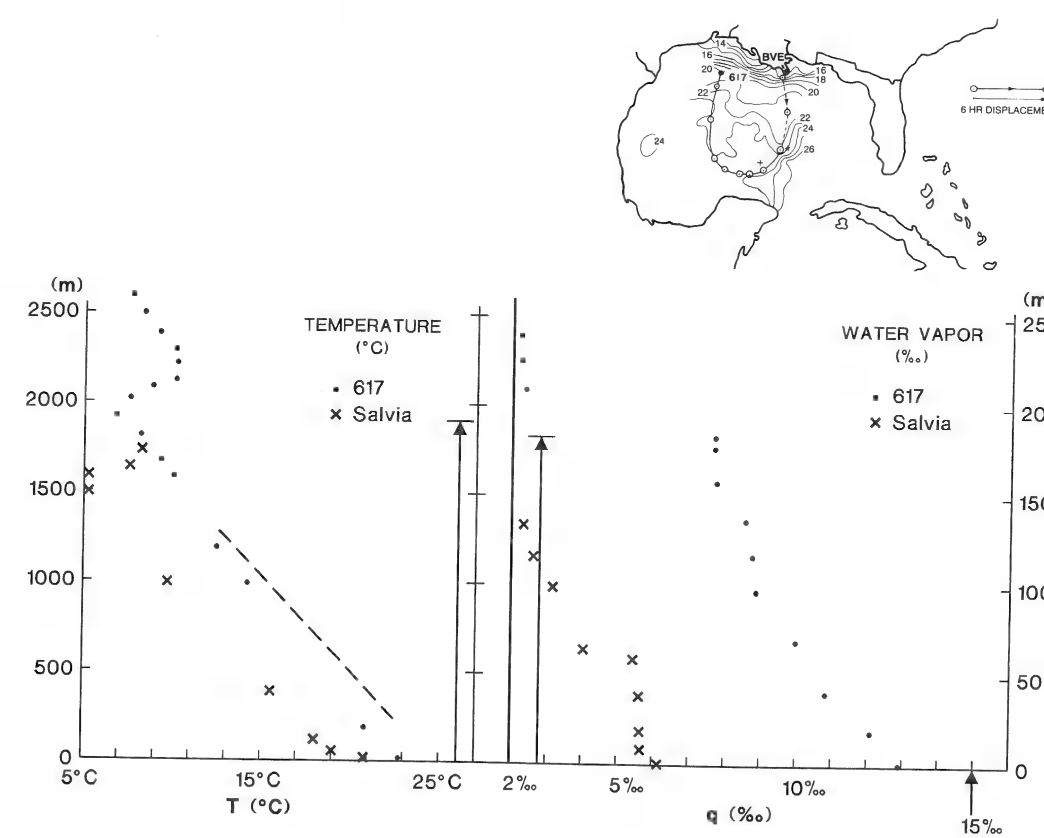
As mentioned in the introduction, accurate prediction of precipitation/severe weather critically depends on the depth (and amount) of vapor returning to the continent. In the absence of upper-air observations over the Gulf, forecasters are forced to make subjective judgments inferred from satellite cloud imagery (if clouds indeed do form) and data from instrumented buoys (that do not measure water vapor because of attendant difficulties associated with sea spray). The presence of cloud often delineates the leading edge of the vapor-laden air from the drier air to the north; yet the depth of the mixed layer, over which the clouds usually form, is known very inaccurately and the quantity of vapor is subject to further erroneous estimation. Two independent studies of inaccuracies in the operational prediction of these cool season return flows have been conducted by Weiss (1992) and Janish and Lyons (1992).

During both field experiments (1988/1991), our data were made available to the NWS forecasters at the U.S. National Severe Storms Forecast Center (NSSFC) and at NWS offices in the southern United States. Unfortunately, we were unable to transmit the data to Mexico in a timely fashion.

The 1991 data from Mobil 617 were especially valuable for the case of an exceptionally strong extratropical cyclone that moved into Kansas on March 13. The operational models made an accurate prediction of the movement of the cyclone, but there was uncertainty concerning the amount of water vapor associated with this event. The NSSFC forecasters, required to issue 48 h outlooks of severe weather, issued the following statement on March 11:

> While dynamics are favorable for severe thunderstorm development . . . uncertainty exists about degree of moisture return and instability. 12Z [6 am, CST] sounding from the Gulf of Mexico Project revealed limited moisture over the northern Gulf of Mexico. This sounding located at ~28°N, 93°W showed surface dewpoints only in the mid-thirties [q ≐ 3-4 g kg^{-1}] . . .

FIGURE 9. Profiles of temperature (°C) and water vapor (g kg^{-1}) from CLASS units in the Gulf of Mexico. The *Salvia* data represent air that has moved from the coast to the Loop Current. Data from Mobil 617 are representative of the further modification of the air as it moves from the Loop Current to the edge of the continental shelf. The inset shows the trajectory of surface air as it was tracked from the Gulf coast through the Loop Current region and back to Mobil 617.

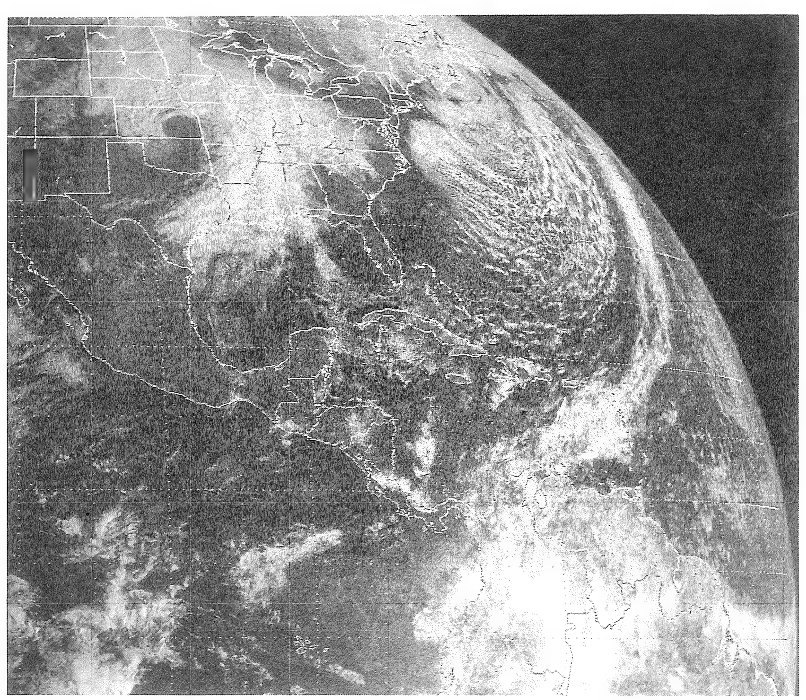


Because of the limited water vapor, there were no severe storms on March 11th or 12th. Some severe storms did develop over the Mississippi Valley on the 13th. The forecast was difficult because this cyclone was the most intense of the 1991 spring season. If dewpoints had reached the mid-50s (°F) or higher ($q \sim 8$ g kg^{-1} or higher), a severe storm outbreak would have been likely. The cloud mass associated with this extratropical cyclone when it was centered over Kansas at 9:00 pm CST (1500 UTC) on March 12, 1991, is shown in Figure 10.

SUMMARY

During the cool seasons (February-March) of 1988 and 1991, the National Severe Storms Laboratory spearheaded field experiments over the Gulf of Mexico that made use of the Loran-C tracked upper-air sounding system (CLASS). We found that this upper-air system is ideally suited to the constraints encountered at sea, viz., moving platforms (ships) and space-restricted/obstacle-laden platforms (oil-rig platforms). To be sure, there are difficulties in these environments. These difficulties have been enumerated for the oil-rig platform, and with minimal effort, they were overcome. Problems aboard the ships were less severe and could be considered a subset of the problems dealt with on the platform.

FIGURE 10. Visible imagery from the GOES weather satellite at 1501 UTC, March 12, 1991. The cloud pattern clearly depicts the counter-clockwise rotation around the intense extratropical cyclone centered over Kansas



The CLASS soundings have allowed us to quantitatively determine the rate of heating and moistening that takes place as the cold/dry air masses move over the relatively warm waters of the Gulf in the cool season. It has also been demonstrated that a lone upper-air sounding on the edge of the continental shelf played a decisive role in the forecast for severe weather associated with an extreme extratropical cyclone event in 1991.

ACKNOWLEDGMENTS

Robert A. Millikan (1873-1952), former Chief Executive of the California Institute of Technology, said: "Make your science relevant to the needs of society." In this admonition, he implied that researchers should work alongside private enterprise and government agencies to accomplish common goals that are linked to societal concerns. In this spirit of Robert Millikan, those of us at NSSL who participated in the field experiments (Charlie Crisp, Sherman Fredrickson, Paul Griffin, John Lewis, and Les Showell) wish to express our deepest gratitude to the Mobil Oil Company, the U.S. Coast Guard, the National Center for Atmospheric Research, the Mexican and U.S. Weather Services, and the U.S. Air Force for their Herculean efforts to facilitate the acquisition of upper-air observations over the Gulf of Mexico and to thereby contribute to improved weather forecasting—an unquestionable benefit for the citizenry of both the United States and Mexico.

Technical assistance from NSSL's chief secretary, Joy Walton, and graphics artist, Joan O'Bannon, is also acknowledged.

REFERENCES

Beukers, J.M. 1978. The use of LORAN and VLF navaids for windfinding. In: *Atmospheric Technology*, Winter 1978–79, pp. 3–13. Boulder, Colorado: National Center for Atmospheric Research.

Bowditch, N. 1802. *American Practical Navigator*, vol. 1 (1977 edition). Defense Mapping Agency Hydrographic Center, Wash. D.C., 20390 (Attn. Code PR), Pub. No. 9, 1386 pp.

Crisp, C.A. and Lewis, J.M. 1992. Return flow in the Gulf of Mexico. Part I: A classificatory approach with a global historical perspective. *J. Applied Meteor.*, 31(8): 868–881.

Garrett, W.B. (Ed.) 1981. *National Geographic Atlas of the World*. Nat. Geogr. Soc., 383 pp.

Janish, P.R. and Lyons, S.W. 1992. NGM performance during cold-air outbreaks and periods of return flow over the Gulf of Mexico with emphasis on moisture-field evolution. *J. Applied Meteor.*, 31(8):995–1017.

Journal of Applied Meteorology. 1992. Air-Sea Interaction and Air Mass Modification over the Gulf of Mexico. Special Issue, August 1992, 31(8):819–1020.

Lauritsen, D., Malekmadani, C., Morel, C. and McBeth, R. 1987. The cross-chain LORAN atmospheric sounding system (CLASS). In: *Preprints Sixth Sym. Meteor. Observ. and Inst.*, pp. 340–343. New Orleans: American Meteorological Society.

Lewis, J.M. and Crisp, C.A. 1992. Return flow in the Gulf of Mexico. Part II: Variability in return-flow thermodynamics inferred from trajectories over the Gulf. *J. Applied Meteor.*, 31(8):882–898.

Lewis, J.M., Hayden, C.M., Merrill, R.T. and Schneider, J.M. 1989. GUFMEX: A study of return flow in the Gulf of Mexico. *Bull. Amer. Meteor.* Soc., 70:24–29.

Passi, R.M. and Morel, C. 1987. Wind errors using worldwide Loran network. *J. Tech.*, 4:690–700.

Rasmusson, E.M. 1967. Atmosphere water vapor transport and the water balance of North America: Part I. Characteristics of the water vapor flux field. *Mon. Wea. Rev.*, 95:403–426.

Rust, W.D. and Marshall, T.C. 1989. Mobile, high-wind, balloon launching apparatus. *J. Tech.*, 6:215–217.

Sanders, M.J. and Barr, W.A. 1978. National Weather Service radiotheodolite windfinding systems. In: *Atmospheric Technology*, Winter 1978–79, pp. 36–40. Boulder, Colorado: National Center for Atmospheric Research.

Smalley, J.H. 1978. Aircraft dropwindsonde system. In: *Atmospheric Technology*, WInter 1978–79, pp. 24–28. Boulder, Colorado: National Center for Atmospheric Research.

Weiss, S.J. 1992. Some aspects of forecasting severe thunderstorms during cool-season return-flow episodes. *J. Applied Meteor.*, 31(8):964–982.

U.S. Navy. 1986. U.S. Navy climatic study of the Caribbean Sea and Gulf of Mexico, Vol. 1–4, NAVAIR 50–1C–546, prep. under Commander, Naval Wea. Ser. Com., NSTL, MS, 39529–5000, ea. vol. approx. 200 pp.

PAPER

Marine Ecosystems: Assessing the Impacts of Chronic Contamination from Offshore Platforms

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ABSTRACT

An integrated, multidisciplinary investigation is testing for biological impacts in the vicinity of long-term oil and gas production sites in the Gulf of Mexico. The objective is to develop methods to assess sublethal effects of chronic exposure of marine organisms to contaminants discharged from offshore platforms. The chemical/physical components provide information on the spatial and temporal distribution of pollutants. The biological components identify responses to chronic chemical contamination as reflected in biochemical detoxification, life history, reproductive success and effort, and assemblage composition. From these biological components, early-warning indicators of contaminant exposure will be selected and refined in future studies. Ultimately, these indicators may be incorporated into standard procedures for monitoring offshore platforms.

INTRODUCTION

The Minerals Management Service (MMS) is responsible for managing and regulating oil and gas drilling and production on the Outer Continental Shelf (OCS) of the Gulf of Mexico. This region has a long history of exploration, development, production, and transportation. While acute, toxic effects of these activities are well understood and considered to be site-specific and transitory, knowledge regarding more subtle effects associated with chronic exposure to oil and gas development and production activity is poor (Boesch and Rabalais, 1987).

The Gulf of Mexico Offshore Operations Monitoring Experiment (GOOMEX) Phase I was designed and initiated by the MMS to develop environmental indicators of chronic, sublethal contamination associated with oil spills and discharges of produced water, drilling muds, and cuttings on the OCS. GOOMEX was competitively awarded to the Geochemical and Environmental Research Group (GERG) of Texas A&M University, where an interdisciplinary team of investigators is conducting studies that will measure biological responses from the molecular to the community level (Table 1).

Information derived from GOOMEX assists the MMS in fulfilling its mandate under the OCS Lands Act Amendments to conduct studies to predict, assess, and manage the effects of OCS activities on the marine environment. The techniques evaluated from Phase I will be refined in future studies into standard monitoring procedures that could be employed during subsequent OCS exploration and development activities. A summary of the program elements found in GOOMEX is presented here.

OBJECTIVE

The objective of GOOMEX is to identify the fundamental detoxification responses of resident fauna resulting from chronic exposure to discharges from long-term OCS production platforms (Kendall and Ray, 1990). In marine environments, these biochemical responses may serve as early warning indicators of more serious damages prior to changes that are manifested at the population or community level.

SAMPLING DESIGN

One of the principal design components of GOOMEX is to quantify natural variability associated with Gulf marine ecosystems. Adequate definition of natural variability is essential to attribute chronic, sublethal perturbations at the molecular, organism, population, and/or community levels to platform discharges. Discerning subtle changes in an ecosystem requires recording parameters not only at the appropriate time scales but also in novel ways that may require the development of new approaches. Large numbers of observations are also needed to provide statistically valid conclusions or interpretations.

Initially, five sites (Figure 1) were selected for study: Mustang Island MI-A85 (site 1), Matagorda Island MIA-686 (site 2), Matagorda Island MIA-622 (site 3), East Flower Gardens HI-A389 (site 4), and Buccaneer Oil and Gas Field GA-288 (site 5). Their selection was based on several criteria including the following: (1) a site must be outside the influence of the Mississippi River plume; (2) active production must have occurred for 10 years or more; and(3) appropriate control sites must be available. Control, or comparison sites, are located away from the influences of any platform, platform group, or pipeline now or in the past. The comparison site is similar to the platform site in water depth, sediment characteristics, physico-chemical setting, ambient current regime, and benthic fauna. Secondary criteria for site selection include the availability of previous historical databases, an appropriate benthic setting for sampling, and proven contaminant gradients. After the initial sampling of the five sites, three will be chosen for more intensive study based on initial results. Three additional cruises will sample each of the three final sites over an 18-month period for a total of four samplings at each site. The sampling design is based on a statistical model that is essential for final data synthesis and analysis (Figure 2).

The experimental designs chosen balance the conflicting demands of cost, time scales, and indicator development. This balance also detects nearfield impacts and contaminant gradients extending out from a given site.

Two designs are necessary to meet program objectives. The first is detailed benthic sediment sampling by boxcore. Boxcores subdivided in 25 subcores will be taken at 25 stations per study site. Subcores are allocated to study elements as illustrated in Figure 3. Benthic sediment stations are allocated along five radii with oversampling within the nearfield. Eighty percent of the sediment sampling is concentrated within 500 m of the platform to define the contaminant field effectively. Sampling over several seasons documents changes induced by contaminant exposure which decreases with increasing distance from the platform (Figure 2). This design also includes sample replication to assess spatial patchiness and analysis of variance to determine directional and distance influences (Batschelet, 1976).

A second study design tests methods that measure responses to contaminant exposure. Sampling of the extremes at the site is used to determine if a response is present. A near/far pair-wise comparison utilizes larger animals (macrofauna and fish) collected by otter trawls within 100 m of the platform (near) and at >3,000 m from the platform (far).

TABLE 1. MMS-sponsored GOOMEX principal investigators and topics of research.

Investigator	Topics of Research
Mahlon Kennicutt II (GERG)	**Program Manager; Management Group Leader**
Roger Green (University of W. Ontario)	Data Analysis
Gary Wolff (GERG)	Data Management
Roger Fay (GERG)	Field Logistics
James Brooks (GERG)	**Chemistry and Sedimentology Group Leader**
Terry Wade (GERG)	Hydrocarbon Analysis
B.J. Presley (GERG)	Trace Metal Analysis
Richard Rezak (Consultant)	Sedimentology
Tamara Davis (GERG)	Ancillary Parameters
Paul Montagna (University of Texas)	**Benthic Biology Group Leader;** Meiofauna; Meiofaunal Bioassay
Don Harper (Texas A&M at Galveston)	Infauna/Epifauna; Macrofaunal Taxonomy
Eric Powell (Texas A&M University)	Macroinvertebrate Life History Immunological Probe
Rez Darnell (Texas A&M University)	**Mobile Invertebrates and Demersal Fish Group Leader;** Fish Food
John McEachren (Texas A&M University)	Demersal Fish Taxonomy
Steve Safe (Texas A&M University)	**Toxicology Group Leader;** Detoxification Response
John Fournie (EPA-Gulf Breeze)	Necropsies & Histopathology
Scott Carr (Fish and Wildlife Service)	Sediment Pore Water Toxicity Testing
Susan McDonald (GERG)	Detoxification Response; Biliary Metabolites
Denis Wiesenberg (GERG)	**Physicochemical Group Leader**
Frank Kelly (GERG)	Hydrography; Water Quality
Pasquale Roscigno (MMS)	Contracting Officer's Technical Representative

Scientific Review Board

Donald Boesch	(University of Maryland System, Cambridge)
Robert Carney	(Louisiana State University, Baton Rogue)
James Ray	(Shell Oil Company, Houston, Texas)
Robert Spies	(Applied Marine Science, Inc., Livermore, California)

SEDIMENTOLOGY-CHEMISTRY

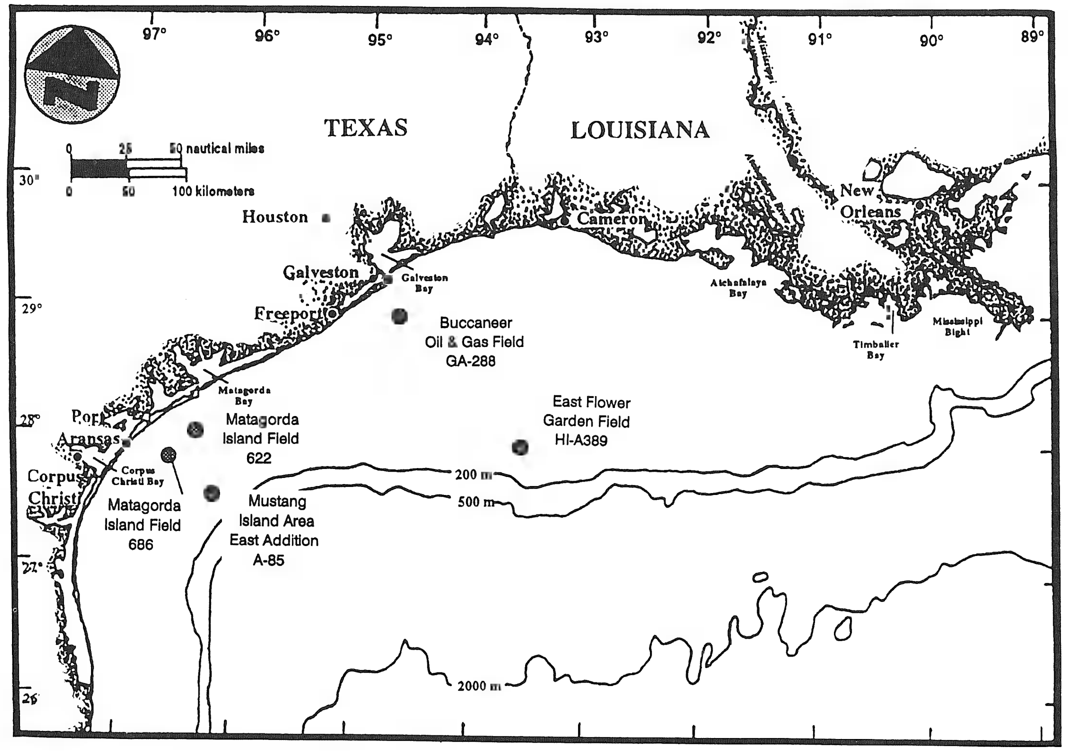
The environmental variables that are collected during this study include water column measurements of temperature, salinity, oxygen, and inorganic nutrients (phosphate, nitrate, nitrite, and silicate). The sediment's grain size and mineralogy are determined for each study location along with total organic carbon, carbonate carbon content, and redox condition. The trace metal, aliphatic hydrocarbon, and aromatic hydrocarbon analytes to be analyzed in sediments and tissues are listed in Table 2. These analyses will be used to characterize the spatial and temporal variability of the contaminant field surrounding the production platforms. The influence of non-contaminant factors, such as grain size, will be evaluated with respect to variations in benthic biology. All of the methodologies employed in the analytical chemistry component follow protocols developed for the National Oceanic and Atmospheric Administration's National Status and Trends program assuring high quality data that are comparable with data from other environmental programs such as the U.S. Environmental Protection Agency's Environmental Monitoring and Assessment Program (Cantillo and Lauenstein, 1993).

BIOLOGICAL MEASUREMENTS

Benthic Biology

Benthic infaunal organisms are good integrators of contaminant exposure because of their intimate association with the substrate, their relative immobility, and their specialized

FIGURE 1. Location of study sites.



filter-feeding strategies. While shallow water environments are influenced by seasonal variations in temperature and salinity, benthic assemblages can be classified into broad classifications based on depth. The inner shelf assemblage extends from 0 to 20 m depth overlapping with the pro-delta assemblage (4 to 20 m). Other assemblages are the intermediate shelf assemblage (20 to 60 m); an outer shelf assemblage (60 to 120 m); and an upper slope assemblage (120 to 200 m) (Chittenden and McEachran, 1976; Defenbaugh, 1976; Moore et al., 1970).

Meiobenthic organisms pass through a 0.5-millimeter (mm) sieve but are retained on a 0.063-mm sieve. These organisms serve particularly important ecological niches in habitats with processes operating at spatial and temporal time-scales that make them ideal organisms for studying platform-associated impacts (Bell, 1980). The community abundance and structure and life-history studies for harpacticoids, a major meiofaunal component, are conducted at all stations in order to determine the impact of contaminants on species diversity, abundance, and reproductive effort. For every individual of three meiofauna species the following are measured: size, copepodite stage, sex, gravid females, number of eggs/gravid female, size of eggs, and clutch volume. Mobile invertebrates are collected for reproductive studies and analyses of trace metal and hydrocarbon for body burdens. The sample collection areas are chosen at the maximum exposure in the nearfield for comparison with farfield, unexposed populations. Selected invertebrates are measured for size, gonadal indices (weight and histology), stage of reproductive cycle, sex, egg size, and egg number. An immunological probe is also being developed to measure the rate of gonadal protein production in crabs and scallops.

Demersal Fish

Demersal fish are to provide biological tissues for necropsies, biliary metabolites, inducible enzyme studies, stomach analyses, and contaminant analyses. Fish exhibiting gross pathological disorders, such as fin erosion, somatic ulcers, cataracts, and axial skeletal abnormalities, can serve as indicators of long-term contaminant exposure (O'Connor et al., 1987; Buhler and Williams, 1988; Capuzzo et al., 1988). These fish pathology studies are complemented by histopathological examinations of randomly selected individuals of a common fish species at each site in order to assess the relationship between external abnormalities and internal histopathological information.

Representatives of fish that are sediment feeders, bottom scavengers, and predators are analyzed for levels of contamination in their liver tissue and stomach contents. Because fish livers metabolize polycyclic aromatic hydrocarbons (PAHs) into a variety of intermediate metabolites (Varanasi and Gmur, 1981), assessing hydrocarbon contamination in fish is better accomplished by analyzing the bile of fish for these metabolites (Statham et al., 1976) where they are stored and excreted from the gall bladder. Fish exposed to contaminated sediments have elevated biliary concentrations of PAH metabolites as compared with fish species taken from less contaminated locations (Varanasi et al., 1989).

Detoxification and Toxicological Studies

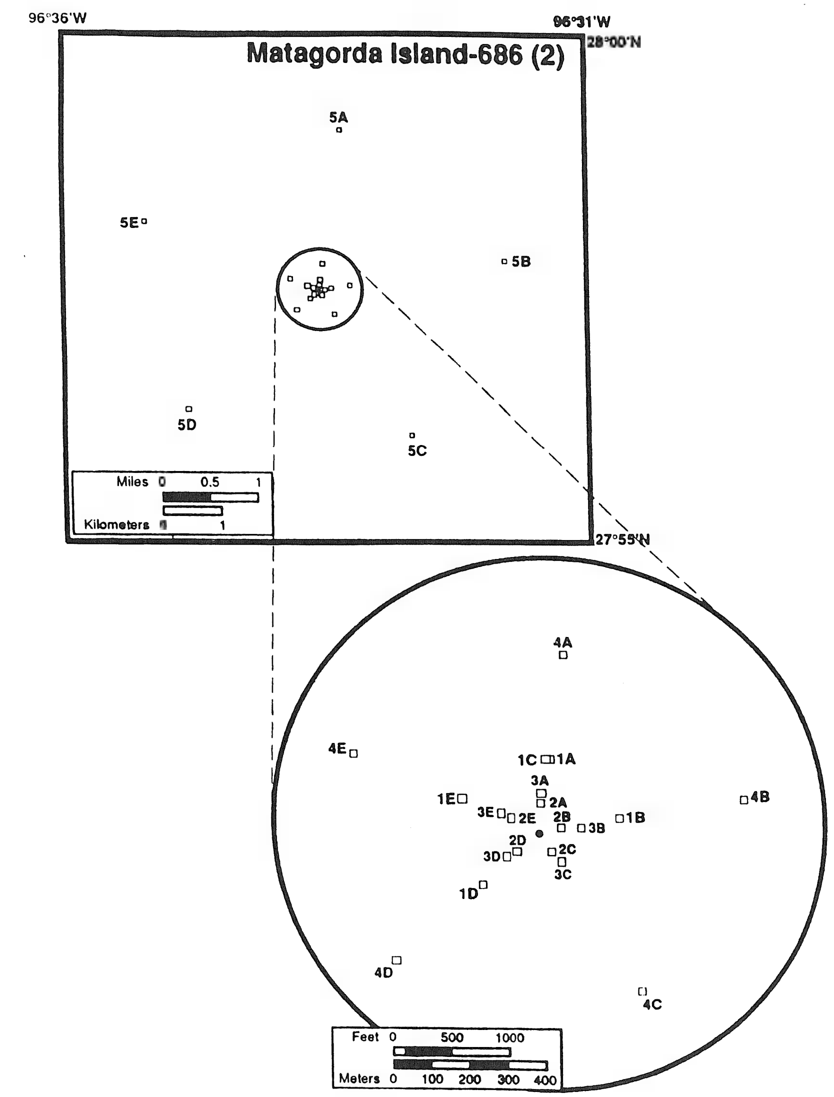
Biochemical responses, genotoxicity, and measurements of anatomical and cytological abnormalities are biomarkers that occur in tissues of animals that have been chronically exposed to contaminants. Detoxification responses are being monitored by a combination of in situ and in vitro techniques. The in situ techniques measure the induction of an enzyme system within native exposed organisms. In vitro techniques utilize invertebrates as accumulators of toxicants that can be subsequently extracted and tested against sensitized cell lines. The induction of the cytochrome P450 mixed function oxidase system (MFO) upon exposure to hydrocarbons is potentially a valuable tool to assess environmental impacts. The MFO activity is measured in demersal fish sampled from the study sites (Stegeman, 1985; Stegeman and Kaplan, 1981; Stegeman and Binder, 1979). Cytochrome P450 content, aryl hydrocarbon hydroxylase activity, and ethoxyresorufin O-deethylase activity are emphasized. In vitro techniques include rat hepatoma H-4-II E cell line bioassay.

Along with MFO biomarkers, sediment pore water toxicity testing provides insight into subtle contaminant effects that do not produce immediate lethality. The interstitial water of sediment is in equilibrium between the water and solid phases, partitioning a toxicant in the environment. It has been suggested that pore water contaminants are more reflective of bioavailable contaminants than bulk sediment measurements. Toxicity testing of pore water is performed using sea urchin sperm mortality and morphological development testing as assessment endpoints (Long et al., 1990). Toxicity tests are also being developed using indigenous harpacticoid copepods.

Invertebrate Reproductive Effort and Life History

Harpacticoid copepods are ideal for studying the impacts of long-term exposure to contamination because their life history and

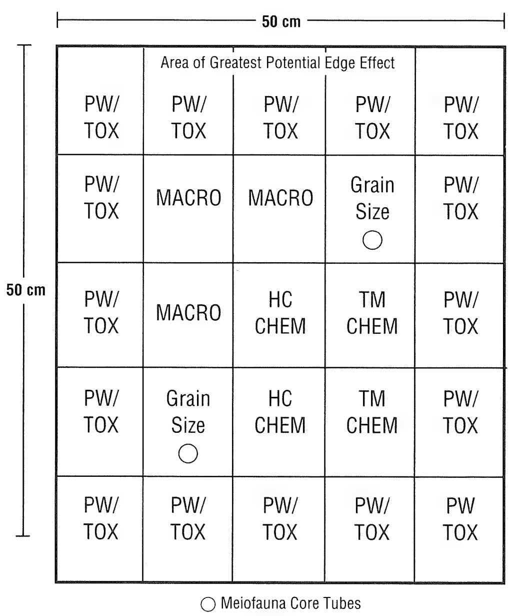
FIGURE 2. Sampling design for study sites.



reproductive efforts are easy to identify and quantify. Their life-cycle produces sexual dimorphic adults and females that brood eggs externally. Their diverse community structure is sensitive to hydrocarbons and barium so that changes in structure and functioning of harpacticoid communities can serve as indicators of contaminant exposure (Hennig et al., 1983; Coull, 1972; Montagna et al., 1989).

In addition, an immunological probe has been developed for oysters and will be applied to other taxon (i.e., crabs, scallops) to serve as an estimate of reproductive effort. These probes provide rates for the synthesis of gonadal protein and may be sensitive assays for measuring reproductive success in invertebrates. Rabbits are injected with purified gonadal tissue so that these animals develop

FIGURE 3. Box core illustrating "vegematic" partitioning. Subsamples will be assigned by a stratified random approach. (MACRO: macroinfauna; PW/TOX: pore water toxicity testing; HC CHEM: hydrocarbon chemistry; TM CHEM: trace metal chemistry; GRAIN SIZE: grain size).



antibodies to the foreign protein. These antibodies are then isolated and used in a radioimmunoassay to bind with egg and sperm protein that has been labelled with radioactive leucine. The antibody and protein complex can be easily assayed with liquid scintillation counting to give estimates of the rate of reproductive growth and of the ratio of growth to reproductive effort (Choi et al., 1990).

SUMMARY

Understanding the complex interactions between marine organisms and their environment requires an understanding of the processes that support their food webs. GOOMEX attempts to examine the biochemical responses of these organisms to exposure to contaminants. Results from this study will be used to assess the role of contaminants in altering the processes that govern the structure and function of marine ecosystems. This knowledge may be incorporated into the design of future programs to monitor the activities associated with offshore platforms.

ACKNOWLEDGMENTS

We thank the reviewers for helpful comments. This paper is dedicated to the memory of J. Kenneth Adams.

TABLE 2. Chemicals measured in the GOOMEX program.

Polycyclic Aromatic Hydrocarbons	
2-ring	**6-ring**
Biphenyl	Benzo(ghi)perylene
Naphthalene	Indeno(1,2,3-cd)pyrene
1-Methylnaphthalene	
2-Methylnaphthalene	
2,6-Dimethylnaphthalene	**Sulfur Aromatics**
1,6,7-Trimethylnaphthalene	Dibenzothiophene
C_1-C_4 Naphthalenes	C_1-C_3 Dibenzothiophenes
3-ring	
Fluorene	**Aliphatic Hydrocarbons**
Phenanthrene	C_{10}-C_{34} normal Alkanes
1-Methylphenanthrene	Pristane
Anthracene	Phytane
Acenapthene	Unresolved Complex Mixture
Acenaphthylene	
C_1,C_2,C_3 Phenanthrenes/Anthracenes	
C_1-C_3 Fluorenes	
	Trace Elements
4-ring	Antimony
Fluoranthene	Arsenic
Pyrene	Barium
Benza[a]anthracene	Cadmium
Chrysene	Chromium
C_1 Fluoranthenes/Pyrenes	Copper
C_1-C_4 Chrysenes	Iron
	Lead
	Manganese
5-ring	Molybdenum
Benzo(a)pyrene	Nickel
Benzo(e)pyrene	Selenium
Perylene	Silver
Dibenz(a,h)anthracene	Tin
Benzo(b)fluoranthene	Vanadium
Benzo(k)fluoranthene	Zinc

REFERENCES

Batschelet, E. 1976. *Introduction to Mathematics for Life Sciences.* New York: Springer-Verlag.

Bell, S.S. 1980. Meiofauna-macrofauna interactions in a high salt marsh habitat. *Ecol. Mono.*, 50: 487-505.

Boesch, D.F. and Rabalais, N.N. (eds). 1987. *Long-Term Environmental Effects of Offshore Oil and Gas Development.* New York: Elsevier Applied Science. 708 pp.

Buhler, D.R. and Williams, D.E. 1988. The role of biotransformation in toxicity. *Aquat. Toxicol.*, 11: 19-28.

Cantillo, A.Y. and Lauenstein, G.G. 1993. Performance based quality assurance of the NOAA National Status and Trends Project. In: *Proceedings of the 5th Internatl. Symp. Harmonization of Internal Quality Assurance Schemes for Analytical Laboratories*, July 22-23, 1993, Washington, DC.

Capuzzo, J.M., Moore, M.N. and Widdows, J. 1988. Effects of toxic chemicals in the marine environment: Predictions of impacts from laboratory studies. *Aquat. Toxicol.*, 11: 303-311.

Chittenden, M.E. and McEachran, J.D. 1976. Composition, ecology and dynamics of demersal communities on the northwestern Gulf of Mexico continental shelf, with a similar synopsis for the entire Gulf. Texas A&M University Sea Grant Publication TAMAU-SG-76-298.

Choi, K.S., Lewis, D.H. and Powell, E. N. 1990. Quantitative evaluation of gonadal proteins in male and female oysters (*Crassostrea virginica*) using an immunological technique. *J. Shellfish Res.* 8: 431-436.

Coull, B.C. 1972. Species diversity and faunal affinities of meiobenthic Copepoda in the deep sea. *Marine Biology*, 14: 48-51.

Defenbaugh, R.E. 1976. A study of the benthic macroinvertebrates of the continental shelf of the northern Gulf of Mexico. Ph.D. thesis, Texas A&M University, College Station, 476 pp.

Hennig, H.F.K.O, Eagle, G.A., Fielder, L., Fricke, A.H., Gedhill, W.J., Greenwood, P.J. and Orren, M.J. 1983. Ratio and population density of psammolittoral meiofauna as a perturbation indicator of sandy beaches in South Africa. *Environ. Monitor. Assess.*, 3: 45-60.

Kendall, J.J. and Ray, J.P. 1990. Detection of impacts associated with long-term oil and gas activity sites. In: *Proceedings* of Workshop. Aug. 15-17, 1989, pp. 115-121. New Orleans: Minerals Management Service.

Long, E.R., Buchman, M.R., Bay, S.M., Breteler, R.J., Carr, R.S., Chapman, P.M., Hose, J.E., Lissner, A.L., Scott, J. and Wolfe, D.A. 1990. A comparative evaluation of five toxicity tests with sediments from San Francisco and Tomales Bay, California. *Environ. Toxicol. Chem.* 9: 1193-1214.

Montagna, P.A., Bauer, J.E., Hardin, D. and Spies, R.B. 1989. Temporal variability and the relationship between benthic meiofaunal and microbial populations of a natural coastal petroleum seep. *J. Mar. Res.* 45: 761-789.

Moore, D., Livingstone, D.R. and Trent, L. 1970. Relative abundance, seasonal distribution, species composition of demersal fishes off Louisiana and Texas, 1962-1964. *Contrib. Mar. Sci.*, 15: 45-70.

O'Connor, J.S., Ziskowski, J.J. and Murchelano, R.A. 1987. Index of pollutant-induced fish and shellfish disease. National Oceanic and Atmospheric Administration Special Report. NDS, Rockville, Md.

Statham, C.N., Melancon, M.J. and Lech, J.J. 1976. Bioconcentration of xenobiotics in trout bile: A proposed monitoring aid for some waterborne chemicals. *Science*, 193: 680-681.

Stegeman, J.J. 1985. Benzo[a]pyrene oxidation and microsomal enzyme activity in the mussel (*Mytilus edulis*) and other bivalve mollusc species from the western *North Atlantic. Mar. Biol.*, 89: 21-30.

Stegeman, J.J. and Binder, R.L. 1979. High Benzo[a]pyrene activity in the marine fish Stenotomus versicolor. Biochem. Pharmacol., 28: 1686-1688.

Stegeman, J.J. and Kaplan, H.B. 1981. Mixed-function oxygenase activity and benzo[a]pyrene metabolism in the barnacle Balanus eburmeus (*Crustacea: Cirripedia*). *Comp. Biochem. Physiol.*, 68C: 55-61.

Varanasi, U. and Gmur, D.J. 1981. Hydrocarbons and metabolites in English sole (*Parophrys vetulus*) exposed simultaneously to [^{3}H] benzo[a]pyrene and [^{14}C] naphthalene in oil contaminated sediment. *Aquat. Toxicol.*, 1: 49-67.

Varanasi, U., Chan, S.-L., McCain, B.B., Landahl, J.T., Schiewe, M.H., Clark, R.C., Brown, D.W., Myers, M.S., Krahn, M.M., Gronlund, W.D. and MacLeod,W.D. Jr. 1989. National Benthic Surveillance Project: Pacific Coast, Part II. Technical presentation of the results for cycles I to III (1984-1986). NOAA Tech. Memo. NMFS F/NWC-170, 159 pp.

PAPER

Dynamics of Dimethylsulfide in Coastal Waters and the Marine Atmosphere: A Need for Platform Observations

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ABSTRACT

Time series measurements of dimethylsulfide in seawater and in the atmosphere will yield valuable insight into the variability of and the controls on this rapidly cycling and important biogeochemical compound. It is vitally important to have access to a stable platform that will allow measurements during periods of high wind speed when gas exchange is rapid and when shipboard measurements are impossible. Assessment of ancillary parameters in the water will increase our understanding of the biological and physical factors influencing DMS cycling in seawater. Simultaneous measurements in the surface water in the atmospheric boundary layer will allow evaluation of sea-air flux models and will aid in unravelling the proposed climate feedbacks associated with DMS.

INTRODUCTION

Dimethylsulfide (DMS) is produced by biological processes in the surface ocean and is the most abundant volatile sulfur gas in seawater. The flux of DMS from the sea to atmosphere is the largest source of natural sulfur to the atmosphere (Lovelock et al., 1972; Liss and Slater, 1974; Andreae and Raemdonck, 1983; Bates et al., 1987). It has been proposed that the oxidation of DMS in the atmosphere results in sub-micron sulfate particles (Shaw, 1983; 1987) or cloud condensation nuclei, forming a long-term climate feedback mechanism through control of planetary albedo (Charlson et al., 1987). The presence of aerosols and clouds may act to moderate the effects of warming induced by other greenhouse gases such as CO_2, CH_4, and N_2O. In addition to this possible role in cloud nucleation, the oxidation products may also serve to return sulfur from the sea to land in the form of biogenic acid rain. The importance of DMS in the coastal zone is underscored by its definition as a focus within the International Geosphere-Biosphere Programme's Land-Ocean Interactions in the Coastal Zone (LOICZ: Holligan and de Boois, 1993)

The concentration of DMS in seawater (usually <5 nmol/L in oligotrophic water, up to perhaps 100 nmol/L in some coastal waters) is 3 to 6 orders of magnitude higher than the equilibrium concentration in the atmosphere and, for purposes of any flux estimate, the atmosphere is an infinite sink with no gradient feedback to dampen the physical process of efflux. However, the physical flux to the atmosphere is not the sole sink for oceanic DMS; removal from the water column also occurs via biological and photochemical processes.

DMS is best viewed as a biological intermediate since it is formed and consumed by organisms. Its residence time in seawater is estimated to be on the scale of hours to days, not much more than its residence time in the atmosphere. The pool of DMS in the oceanic mixed layer is 1 to 30 times the pool of DMS in the overlying atmospheric boundary layer. In coastal waters this ratio is certainly much higher at times. The rapid turnover of the massive seawater DMS pool suggests that relatively minor changes in one of its source or sink terms can lead to a substantial change in concentration and therefore in flux. Our knowledge of these processes and the organisms that carry them out is only moderately quantitative for a very limited set of conditions, and we cannot generate predictive models, be they mechanistic or simply correlative.

DMS PRODUCTION AND CONSUMPTION

Dimethylsulfide in the marine environment appears to be almost exclusively the breakdown product of a sulfonium compound, dimethylsulfoniopropionate (DMSP). DMSP is especially abundant in certain classes of phytoplankton, most notable are the Prymnesiophytes (including coccolithophores and Phaeocystis) and dinoflagellates, and is reputed to play a role as an osmoticum in these organisms (intracellular concentrations can reach 100's of mmol/L cell volume). There is evidence in phytoplankton and bacteria that DMSP levels rise in certain species when exposed to increased salinity. (Vairavamurthy et al., 1985; Visscher and van Gemerden, 1991).

DMSP-bearing phytoplankton release DMS in culture, although evidence is increasing that it is the release of DMSP by these phytoplankton, whether during cell lysis in late stages of a bloom or during zooplankton grazing (Dacey and Wakeham, 1986), which ultimately results in the formation of DMS. Kinetics experiments suggest that dissolved DMSP (dDMSP) in the water column (with concentrations in the same range as DMS) is the major precursor of DMS (Wakeham et al., 1987; Dacey and Blough, 1987; Kiene and Service, 1991; Ledyard, 1993).

The conversion of dDMSP to DMS is accomplished by certain bacteria which use the resultant acrylic acid residue as a carbon source for heterotrophic growth. Under certain circumstances, presumably with different bacterial populations, dDMSP is converted to products other than DMS (Taylor and Gilchrist, 1991).

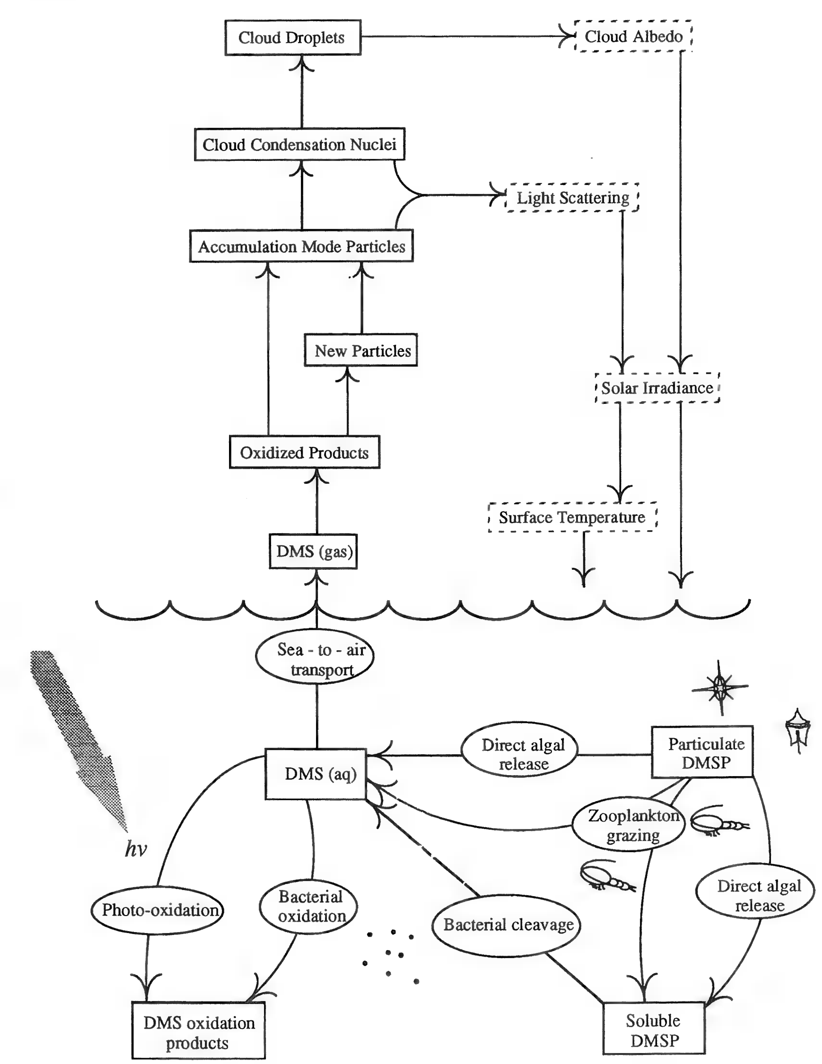
Not only are bacteria important in formation of DMS, but also they may be important in its removal from the water column. Biological oxidation has been heralded as rivalling the flux of DMS to the atmosphere (Kiene and Bates, 1990), though the generality of that finding has not been established. A further sink in surface water is via photochemical oxidation, perhaps with singlet oxygen, which has also been quantified to have a potentially similar rate to gas exchange (Brimblecombe and Shooter, 1986). DMS also leaves the surface water by escaping to the atmosphere across the water surface at a rate determined largely by the wind speed.

When discussing the link between biology and DMS formation, it is important to remember that the biological processes are part of a complex web of interacting processes. The putative link between light and DMS formation invoked in any positive (or homeostatic) climate feedback mechanism is actually mediated through changes in the DMSP content of the phytoplankton pool. DMSP and chlorophyll do not correlate well latitudinally across oceans, nor within individual depth profiles. Changes in phytoplankton production may not be relatable to DMS formation if the species composition of the phytoplankton changes. Ultimately, the formation of DMS appears to depend on release of DMSP by zooplankton grazing and bacterial decomposition of that DMSP. Each step in the biological cycle is influenced by climate. The significance of processes such as warming and wind events on the overall formation and efflux of DMS will vary over time and space scales. The water column processes and their interactions are summarized in Figure 1, which also shows aspects of the cycling of DMS in the marine atmosphere.

THE DMS OCEAN-ATMOSPHERE LINK

Clearly the picture for DMS dynamics is equally complex in the atmosphere. DMS residence time in the atmosphere is measured in days, so boundary layer concentrations must reflect DMS dynamics in the upper ocean. A variety of factors influence the rate of DMS oxidation in the atmosphere, including pollution and solar radiation. Our understanding of the atmospheric processes leading to albedo control is limited, such that even predicting the response to a change in DMS flux is not straightforward. The situation is complicated by anthropogenic influences on many of the atmospheric components, which affect not only the concentrations of the individual species but also the atmospheric chemistry and cloud physics affecting the oxidation of all the reduced species. It is clear that sulfur cycling close to the continents is dominated by these effects (Falkowski et al., 1992), such that any natural feedback system has been overwhelmed. More observations of the variation of the chemical species and of their response to climatological variability are required to help predict their longer term climatic roles.

FIGURE 1. The DMS cycle in the surface ocean and in the atmospheric boundary layer. DMSP which is concentrated in certain species of phytoplankton is decomposed to DMS by a number of pathways. DMS is oxidized in the water column or escapes to the atmosphere. Once in the atmosphere, DMS is oxidized, potentially yielding aerosol particles and cloud condensation nuclei.



ESTIMATION OF DMS SEA-AIR FLUXES

The gas flux/wind speed relationship is a critical element in determining the DMS sea-air flux and has many uncertainties (Wanninkhof, 1992). Previously published budgets for DMS flux have depended on some very simple assumptions (Liss and Slater, 1974; Andreae and Raemdonck, 1983; Bates et al., 1987). The flux of DMS into the atmosphere is determined primarily by two parameters: the concentration in the surface ocean and the wind-speed dependence of gas exchange. There are simply not many measurements of sea surface DMS available and almost none that are related in any way to concomitant process studies. For modeling purposes, sea surface DMS concentrations have been "mapped" according to oceanic regime or approximated by a correlating property such as incident light. Using these maps, flux estimates have been generated based on wind speed data and surface gas exchange models. These models are biologically oversimplified, but they have proven useful in making crude estimates of the magnitude of contemporary DMS flux to the atmosphere. However, the uncertainties associated with these estimates are on the order of 50%. There are two commonly cited flux estimates: Andreae and Raemdonck (1983) calculate a flux of 40 +/– 20 Tg S/yr, while Bates et al. (1987) calculate a flux of 16 +/– 10 Tg S/yr. These calculations underscore the uncertainties involved, offering a range of 6–60 Tg S/yr in the global sea-air DMS flux between their outside estimates.

Work on a fixed platform will provide opportunities to perform experiments to evaluate gas flux/wind speed relationships, which are the largest source of uncertainty in the above calculations. Different approaches that can be applied include direct flux measurements, micrometeorological methods, oceanic tracer methods and atmospheric tracer methods. Historically, these have been troublesome at sea due to the very specific conditions required for each approach. Direct flux measurements require calm conditions, whereby enclosures can be deployed on the water surface. These enclosures are either swept by a flush gas, and the change in trace species content measured, or applied in a static mode where the trace species accumulate inside. Micrometeorological methods involve measuring the gradient of a trace species above the sea surface, requiring fixed sampling heights, and high analytical precision. The short residence time of DMS in the atmosphere makes this a potentially useful approach. Many of these platforms are tall enough to provide a good height span for measuring a gradient. In addition, the ability to measure repeatedly on a fixed platform will increase the precision of our gradient estimate. Tracer methods involve measuring the changes in sea surface concentration of a suitable added compound (Wanninkhof, 1985) or pair of compounds (Watson et al., 1991). These methods require high analytical sensitivity and predictable ocean dynamics. Atmospheric tracer methods involve following the diurnal variation of a compound such as DMS (Cooper, 1989) in order to calculate an overnight accumulation rate. This approach requires steady meteorological conditions for extended periods, measurement of atmospheric boundary layer height, and lack of local variability in the oceanic source term. The latter approach has not yet been applied under perfect conditions; the limited data that have been obtained suggest that the sea-air DMS flux is most likely at the lower end of the published flux estimates (Cooper, 1989; Saltzman et al., 1993a). Further work under better defined conditions is urgently required.

THE TIME-SERIES APPROACH

There are many questions regarding marine DMS and its flux to the atmosphere, but several aspects of the problem are particularly well suited to a time-series approach. A research program based on a static platform would provide an opportunity to "oversample" the surface water, allowing the first robust evaluation of the temporal scales of variability in surface water over time-scales of hours to days. In addition, coupling these data with measurements of atmospheric DMS would provide estimates of the kinetics of gas emission from surface water. Most importantly, these measurements could be made during intervals of high wind when shipboard measurements are extremely difficult. These periods could be very important in terms of long-term averaged sea-to-air fluxes, due to both a strong wind speed dependence in gas exchange rate and the possibility of enhanced transfer through whitecaps and bubbles (Asher et al., 1990).

Most existing data represent essentially snapshots of DMS at various times of year due to the generally sporadic nature of shipboard sampling. A recent study in the North Sea (Liss, 1993) employed a set of transects to document strong seasonal patterns in DMS concentration in surface waters. One particularly important conclusion of that study was the observation that highest emissions did not coincide with the highest levels of DMS in the water. We have collected a similar data set at the Bermuda Atlantic Time-Series Station, a blue-water site southeast of Bermuda (Howse et al., 1993). In both studies, DMS concentrations show a summer maximum in surface waters. Emissions are highly dependent on wind speed and concentrations depend on mixed layer dynamics (Michaels et al., 1993). We conducted 29 profiles during 1992, and we conclude that this frequency of sampling, though the most detailed time-series study at any one site to date, is inadequate to resolve important aspects of DMS dynamics.

DMS is itself a very dynamic compound, and it is important to understand this variability to quantify the processes controlling DMS in the surface water and to make accurate estimates of sea-to-air flux. Neither of the studies cited above track short-term dynamics in DMS concentration, nor for obvious reasons measure concentrations during windy intervals when emission and mixing may be very rapid. During early spring 1992, as our Bermuda time-series work began, we documented dramatic changes in surface concentrations of DMS over time scales of days. We observed increases in DMS concentration of 3 to 4 fold in 4 days in the top 30 m of the water column during a small plankton bloom (Michaels et al., 1993). Measurements ceased when shipboard sampling was no longer feasible due to wind. Seasonally, sea surface DMS varies by almost a factor of 10 at Bermuda (Howse et al., 1993). Our research suggests that DMS turns over on scales of hours to a day or so. Understanding the distribution of such a rapidly cycling gas clearly requires more data on short temporal and small spatial scales. This would be the major advantage of undertaking continuous measurements at a fixed site; then perhaps a detailed understanding of DMS turnover could finally be achieved.

ANALYTICAL METHODS

Measurements of sulfur gases have been routinely made using gas chromatographic techniques. Because of the low levels (usually in the low nanomoles per liter), volatile sulfur species are usually sparged from solution using an inert gas carrier and focused in a trap. Liquid nitrogen was a traditional cryogen for cold trapping. More recently, the use of polymers such as Tenax GC has ended the need for cryogens. Gases are desorbed from the trap by heating, and passed through a chromatographic column to separate sample constituents before detection and quantification. The most commonly used detector for volatile sulfur species is the flame photometric detector (Farwell and Barinaga, 1986), although many others have been developed (reviewed by Crill et al., 1993). Most recently, fully automated analytical systems have been designed for both atmospheric and oceanic DMS measurement, based on either preconcentration using solid adsorbents (Cooper and Saltzman, 1993; Dacey and Howse, 1993) or extremely sensitive detection systems (Johnson and Bates, 1993). Measurement of atmospheric sulfur gases is also complicated by the need to remove interfering oxidants from the sample stream prior to preconcentration. A recent breakthrough has been achieved in this direction with the development of a high capacity aqueous oxidant scrubber (Saltzman and Cooper, 1989). This is obviously a prerequisite for long-term deployment of atmospheric instrumentation.

Quite clearly, sensitive but durable systems are essential for studying DMS variability with possible unattended operation on offshore platforms. Our seawater system (Dacey and Howse, 1993) has been operating at Bermuda Biological Station for Research since January 1992 for analysis of discrete samples; an atmospheric system (Cooper and Saltzman, 1993) has been deployed continuously on shipboard studies up to six weeks long. Both appear to meet requirements for suitable durability. The seawater system is fully automated, drawing the sample by syringe driver, sparging and quantifying DMS, and expelling the analyzed water to waste. The atmospheric system is also fully automated, alternately preconcentrating air on two Tenax traps while analyzing the other of the two traps. These techniques measure discrete preconcentrated DMS samples rather than monitor DMS continuously. These systems are manually calibrated, with calibration standards replacing the samples. However, the chromatography and detector stability of the system described by Dacey and Howse (1993) is sufficiently reliable to allow development of a truly continuous instrument, and laboratory tests suggest that automated calibration using small injections of gas standards should be feasible with minimum disturbance to the sample stream. The deployment of such continuous, self-calibrating detectors will represent a fundamental advance in characterizing the distribution of this gas in the ocean, and its variability in the marine atmosphere. We believe that it is the essential next step for progress in these areas of research.

Other compounds related to DMS are important to measure for understanding processes controlling DMS in seawater. Neither DMSP, which is the major precursor, nor DMSO, which is an oxidation product of DMS, can be easily quantified directly by gas chromatography, but they are analyzed by converting them to DMS. In the case of DMSP, this is a simple base hydrolysis (Dacey and Blough, 1987). In the case of DMSO, chemical reduction is necessary, using a reducing agent like $TiCl_3$. It is possible to envision a system capable of measuring all of the components of the oceanic DMS/DMSP/DMSO cycle based on successive sparging and reaction steps, with the delivery of reagents controlled by metering pumps. Automation may help eliminate

some of the analytical problems, which may be due to sample-to-sample differences in the reaction conditions. Pumped reagent systems have been standard for shipboard automated analyzers for many years (Strickland and Parsons, 1972), and extremely precise systems for low level trace gas analysis are now being successfully deployed, e.g. for the automated measurement of SO_2 in marine air (Yvon et al., 1991; Saltzman et al., 1993b).

ANCILLARY MEASUREMENTS

DMS is in a class of compounds whose study will benefit substantially by almost any ancillary measurements, because of the biological water column source of DMS, its aqueous photochemistry, the importance of both oceanic and atmospheric transport processes, and the need to quantify its atmospheric chemistry. Determination of the biological and physical structure of the water column would be extremely valuable in interpreting DMS profiles. Our previous work has shown significant structure in DMS and DMSP throughout the surface layer, even when these depth layers might otherwise be thought of as well mixed. Having the kind of precise physical data that might be provided on such a platform will be very useful in investigating the relative contributions of physical and biological processes to these profiles.

Study of atmospheric sulfur cycling from a platform will require routine monitoring of meteorological variables such as wind, temperature, humidity, and pressure. These are especially important in coastal areas, where the relative contributions of marine and continental air need to be determined. This effort would also be aided by measurements of rainwater and aerosol constituents, such as methane sulfonic acid and non-sea-salt sulfate, the atmospheric oxidation products of reduced sulfur gases. In order to study the full atmospheric chemistry of DMS with the aid of photochemical models, it is desirable to have measurements of physical variables, such as insolation and vertical boundary layer structure, and chemical species, such as ozone, NO, NO_2, CO, CH_4 and non-methane hydrocarbons. With the exception of low-level NO and NO_2 measurements, these are all fairly standard procedures. Measurement of the atmospheric vertical structure requires deployment of radiosondes. In this respect, the fixed nature of a platform is particularly useful, since tethered sondes can be used rather than the disposable sondes used in shipboard studies. This allows for simple collection of vertical wind structure in addition to the more standard temperature, pressure, and humidity data. Such data would also aid considerably in deconvoluting marine and continental air mass transport.

In addition to the potential for studying temporal variability, studying water column processes, and evaluating gas exchange algorithms, automated instrumentation on a fixed platform would yield a simple, cheap, and effective way of collecting data to tie in with the ocean color images that will be available after the launch of SeaWIFS in 1994. The platform approach will have considerable advantage over shipboard studies in terms of temporal resolution and, most likely, process studies. Shipboard studies will continue to provide better spatial resolution and allow tracking of watermasses, both of which are important in understanding DMS dynamics. Concepts developed from platform-based work will certainly enhance shipboard studies by bringing the focus to key processes.

REFERENCES

Andreae, M.O. and Raemdonck, H. 1983. Dimethylsulfide in the surface ocean and the marine atmosphere: a global view. *Science* 221: 744–747.

Asher, W.E., Monahan, E.C., Wanninkhof, R. and Bates, T.S. 1990. Correlation of fractional foam coverage with gas transport rates. In: *Proceedings of the Second International Symposium on Gas Transfer*, Minneapolis, MN.

Bates, T.S., Cline, J.D., Gammon, R.H. and Kelly-Hansen, S.R. 1987. Seasonal variations in the flux of oceanic dimethylsulfide to the atmosphere. *J. Geophys. Res.* 92: 2930–2938.

Brimblecombe, P. and Shooter, D. 1986. Photo-oxidation of dimethylsulfide in aqueous solution. *Mar. Chem.* 19: 343–354.

Charlson, R.J., Lovelock, J.E., Andreae, M.O., and Warren, S.G. 1987. Oceanic phytoplankton, atmospheric sulfur, cloud albedo and climate: a geophysiological feedback. *Nature* 326: 655–661.

Cooper, D.J. 1989. Reduced Sulfur Cycling in the Marine Atmosphere, Ph.D. Dissertation, University of Miami.

Cooper, D.J. and Saltzman, E.S. 1993. Measurements of atmospheric dimethylsulfide, hydrogen sulfide and carbon disulfide during GTE/CITE-3, *J. Geophys. Res.*, in press

Crill, P., Butler, J., Cooper, D. and Novelli., P. 1993. Standard analytical methods for measuring trace gases in terrestrial ecosystems and the atmosphere. *Methods in Ecology: Trace Gases*, P. Matson and R.C. Harriss (eds.), in press.

Dacey, J.W.H. and Blough., N.V. 1987. Hydroxide decomposition of DMSP to form DMS. *Geophys. Res. Lett.* 14: 1246–1249.

Dacey, J.W.H. and Howse, F.A. 1993. Automated sparging and analysis of DMS from seawater samples. The Oceanography Society, Third Scientific Meeting, Seattle.

Dacey, J.W.H. and Wakeham, S.G. 1986. Oceanic dimethylsulfide: production during zooplankton grazing on phytoplankton. *Science* 233: 1314–1316.

Falkowski, P.G., Kim, Y., Kolber, Z., Wilson, C., Wirick, C. and Cess, R. 1992. Natural versus anthropogenic factors affecting low-level cloud albedo over the North Atlantic. *Science* 256: 1311–1313.

Farwell, S.O. and Barinaga, C.J. 1986. Sulfur-selective detection with the FPD: Current enigmas, practical usage, and future directions. *J. Chrom. Sci.* 24: 483.

Holligan, P.M. and de Boois, H. 1993. Land-Ocean Interactions in the Coastal Zone, Report #25 of the International Geosphere-Biosphere Programme, Stockholm.

Howse, F.A., Dacey, J.W.H., Michaels, A.F. and Wakeham, S.G. The seasonal cycle of DMS in the Sargasso Sea. The Oceanography Society, Third Scientific Meeting, Seattle, 1993.

Johnson, J.E. and Bates, T.S. 1993. Atmospheric measurements of carbonyl sulfide, dimethyl sulfide and carbon disulfide using the electron capture detector. J. *Geophys. Res.* in press.

Keller, M.D. 1989. Dimethyl sulfide production and marine phytoplankton: the importance of species composition and cell size. *Biol. Oceanog.* 6: 375–382.

Kiene, R.P., and Bates, T.S. 1990. Biological removal of dimethyl sulfide from sea water. *Nature* 345: 702–705.

Kiene, R.P. and Service, S.K. 1991. Decomposition of dissolved DMSP and DMS in estuarine waters: dependence on temperature and substrate concentration. *Mar. Ecol. Prog.* ser. 76:1–11.

Ledyard, K.M. 1993 Marine microbial production of dimethylsulfide from dimethylsulfoniopropionate, PhD Dissertation, MIT/WHOI.

Liss, P.S. and Slater, P.G. 1974. Flux of Gases Across the Air-Sea Interface. *Nature* 247: 181–184.

Liss, P.S. 1993. Exchange between the coastal ocean and the atmosphere. The Oceanography Society, Third Scientific Meeting, Seattle.

Lovelock, J.E., Maggs, R.J. and Rasmussen, R.A. 1972. Atmospheric Dimethylsulfide and the natural sulfur cycle. *Nature* 237: 452–453.

Michaels, A.F., Dacey, J.W.H., Howse, F.A. and Johnson, R. 1993. Short-term variability in springtime DMS and DMSP dynamics at the Bermuda Atlantic Time-series Study site. The Oceanography Society, Third Scientific Meeting, Seattle.

Saltzman, E.S. and Cooper, D.J. 1989. Dimethylsulfide and hydrogen sulfide in marine air. In: *Biogenic Sulfur in the Environment*, E.S. Saltzman and W.J. Cooper, (eds.), ACS Symposium Series 393, pp 330–351, American Chemical Society, Washington.

Saltzman, E.S., Cooper, D.J., Yvon, S.A., Andreae, M.O., Andreae, T.W., Bandy, A.R., Bates, T.S., Davis, D.D., Ferek, R.J., Johnson, J.E., Shipham, M.C. and Shipham, D.C. 1993. Diurnal variations in atmospheric sulfur gases over the western equatorial Atlantic Ocean. *J. Geophys. Res.*, submitted.

Saltzman, E.S., Yvon, S.A. and Matrai, P.A. 1993. Low-level atmospheric sulfur dioxide measurement using HPLC/fluorescence detection. *J. Atmos. Chem.*, in press.

Shaw, G.E. 1983. Bio-controlled thermostasis involving the sulfur cycle. *Clim. Change*, 5: 297–303.

Shaw, G.E. 1987. Aerosols as climate regulators: A climate-biosphere linkage? *Atmos. Environ.* 21: 985–986.

Strickland, J.D.H. and Parsons, T.R. 1972. *A Practical Handbook of Seawater Analysis.* Fisheries Research Board of Canada, Bulletin 167, 310 pages.

Taylor, B.F. and Gilchrist, D.C. 1991. New routes for aerobic biodegradation of dimethylsulfoniopropionate. *Appl. Env. Microbiol.* 57: 3581–3584.

Vairavamurthy, A., Andreae, M.O. and Iverson, R.L. 1985. Biosynthesis of Dimethylsulfide and dimethylpropiothetin by *Hymenomonas carterae* in relation to sulfur source and salinity variations. *Limnol. Oceanogr.* 30: 59.

Visscher, P.T. and van Gemerden, H. 1991. Production and consumption of dimethylsulfoniopropionate in marine microbial mats. *Appl. Env. Microbiol.* 57: 3237–3242.

Wakeham, S. G., Howes, B.L., Dacey, J.W.H., Schwarzenbach, R.P.and Zeyer, J. 1987. Biogeochemistry of dimethylsulfide in a seasonally stratified coastal salt pond. *Geochim. Cosmochim. Acta.* 51: 1675–1684.

Wanninkhof, R., Ledwell, J.R. and Broecker, W.S. 1985. Gas exchange-wind speed relation measured with sulfur hexafluoride on a lake. *Science* 227: 1224–1226.

Wanninkhof, R. 1992. Relationship between wind speed and gas exchange over the ocean, *J. Geophys. Res.* 97: 7373–7382.

Watson, A.J., Upstill-Goddard, R.C. and Liss, P.S. 1991 Air-sea gas exchange in rough and stormy seas measured by a dual-tracer technique. *Nature* 349: 145–147.

Yvon, S.A., Cooper, D.J., Saltzman, E.S. and Quinn, P.K. 1991. Measurements of atmospheric DMS and SO_2 over the Northwest Pacific Ocean during PSI–3. *Eos* 72: 104.

COMMENTARY

Offshore Platforms and Research Opportunities: An Industry Perspective

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INTRODUCTION

Global climate change has been identified within government and the scientific community as a potentially high risk issue due to the possible scale of its impact and the timing required to affect change. One of the weakest links in identifying and assessing the potential risk is availability of data concerning the role of the oceans in moderating climate change. Research in the oceans is of highest priority in understanding this issue and in providing the scientific basis for establishing realistic public policy decisions.

Offshore oil and gas production platforms provide a logical means for research scientists to expand their understanding of ocean communities and their role in global climate patterns. Since these facilities will likely be in place long term, they provide a relatively permanent vantage point for collecting continuous observations in all weather conditions.

BP Exploration (BPX) has offered its platforms in the Gulf of Mexico to be part of a global network of platforms studying the oceans (as discussed later in this article). As a user of the oceans BPX is naturally interested in research that could aid us in understanding them. Also, as a member of an industry that is a focal point of developing environmental policies, we see the need for sound science to answer questions.

Leveraging available resources to aid in understanding the oceans makes sense particularly in these times of diminishing funds. Both government and industry are trying to do more—and do it better—with fewer resources. This linking of industry and the scientific community on offshore platforms makes perfect sense. As evidenced by the rapid advances in offshore performance and technology, we learn and improve by doing. The same can be said within the research community where new opportunities, like research from platforms, provide new ways of answering questions. As a result the science community can provide the sound science for solid decision making. This approach can have the additional benefit of bringing together typically adversarial oil and environmental interests, in a research program of high value to both groups.

PLATFORM TECHNOLOGY

The advanced technology of the offshore industry has developed rapidly. The first offshore wells were drilled in coastal California at the turn of the century. Operations were conducted from a wooden wharf extending only about 91 m (300 ft) into the ocean. By 1947 mobile drilling and production advanced sufficiently for the first significant discovery to be made, out-of-sight of land, in the Gulf of Mexico.

Today's platforms range in size and complexity from single well structures to large manned oil platforms with up to 60 wells. A typical manned platform houses both drilling and production equipment for the first few years until all prospective targets have been drilled. Once those wells are drilled and completed, the rig is removed. On-board production equipment processes the hydrocarbons sufficiently for transportation to shore. Separators split the produced stream into oil, water, and natural gas. The oil, after the water and gas are removed, is transported through a subsea oil pipeline to onshore facilities for further processing and distribution. Ultimately products such as gasoline, diesel, and lubricants are produced. The natural gas is transported through a separate subsea pipeline to onshore distribution systems. The produced water is treated to remove virtually all traces of oil and is discharged overboard. The platforms also contain other facilities, such as living quarters, power generation, and sewage treatment, making the platform a self-contained unit. Personnel living on board can be as many as 70 during simultaneous drilling and production operations, but the number drops to fewer than 10 once routine production is underway.

Safety systems are a critical component of every phase of operations. Systems that automatically shutdown the platform in the event of an upset in the system (e.g., a high level or pressure in the wells, separators, or pipelines) are in place. The potential presence of hydrocarbon vapors requires the use of appropriately designed and intrinsically safe electrical equipment. Equipment with sparking devices or open flames receive careful attention to insure they do not present a hazard and can be strictly limited. Fire and combustible vapor monitors will automatically shut down the process if certain safety limits are exceeded. All systems are designed in accordance with hazardous area regulations of the appropriate electrical codes.

Not only are offshore facilities designed to avoid operational upsets but they are also designed to withstand severe storms. Their inherent ability to continue data collection in all weather conditions is one of the major advantages of using platforms for research.

Ships or other ocean going vessels are generally unable to collect data during major storms. Platforms, however, are designed to withstand the force from a "100 year storm." Such a storm, by definition, would focus on the facility the cumulative impact of one-hour mean winds of 158 km/h (98 mph), gusts up to 206 km/h (128 mph), wave heights of 22 m (72 ft) and related surface and subsurface storm currents.

Current platform designs were tested in the summer of 1992 by Hurricane Andrew. This category IV storm packed winds of 193 km/h (120 mph). Landfall in central Louisiana caused in excess of $10 billion in damage. Immediately before making landfall, the eye of the storm passed over BPX's Ewing Bank 826-A platform located offshore of Louisiana. Crews had been evacuated and the platform shut in for four days while the storm made its way through the Gulf. Despite Andrew's severity no structural damage occurred. Upon reboarding on the fifth day, crews found only minor damage, mainly the result of flying objects dislodged by the strong winds. This was not necessarily the case with some facilities installed in the early 1970s under less strict design criteria. Some of the older structures were severely damaged and, in a few instances, had been toppled. This recent event clearly demonstrates the advances that have been made in platform design as a result of new technology and increased attention to safety and environmental concerns. Modern facility design criteria enable platforms to withstand major storms without experiencing structural damage. This will enable uninterrupted data collection even during adverse weather conditions.

BP EXPLORATION FACILITIES

BP Exploration (BPX) is a relative newcomer to the Gulf of Mexico. We currently operate nine platforms in the waters offshore Alabama, Louisiana, and Texas. These existing platforms, which produce both crude oil and natural gas, are in water depths of 12 to 330 m (40 to 1,100 ft) located 8 to 161 km (5 to 100 miles) from shore. Construction is underway on our newest platform, Viosca Knoll 989, which will be installed and producing by late 1994. This platform will be located on the edge of the Outer Continental Shelf, 193 km (120 miles) southwest of New Orleans. It is designed to handle 40,000 barrels of crude oil and 50 million cubic ft of gas per day. This platform will likely be in place for the next 20 years, until its reserves are depleted, sometime after 2015.

DEEP-WATER DEVELOPMENT

Production facilities are moving into deeper and deeper waters to support new discoveries. Current technology will allow facilities to be installed in water depths of 1,219 m (4,000 ft) and more. The major challenge to installing deep-water facilities is one of economics rather than technology. Deepwater exploration and development is more costly, requires a greater lead time, and involves a higher degree of financial risk than previous developments on the continental shelf. But deep water also provides the greatest potential for finding large hydrocarbon reserves. Industry and government are working on concepts that will allow these deep-water reserves to be economically and safely developed.

The presence of platforms in deep water can provide ocean researchers an unprecedented opportunity to study ocean dynamics and ecosystems. Information that is simply too difficult or expensive to acquire using conventional ocean vessels will be available. There will be many opportunities for industry, government, and academia to collaborate in understanding the deep ocean environment.

ECONOMIC IMPACT OF PLATFORMS

The offshore oil and gas production industry provides the nation critical revenues and energy supplies. The most recent Minerals Management Service (MMS) document, *Federal Offshore Statistics*, states that about 12 percent of the total U.S. crude production and 24 percent of U.S. natural gas comes from facilities located in the Outer Continental Shelf (OCS) (Minerals Management Service, 1991). The Gulf of Mexico OCS region is the most active. At the end of 1991 there were over 3,800 producing platforms in place in the Gulf of Mexico.

This translates into a significant source of revenues for the federal government. OCS leasing and production are one of the largest sources of funds for the federal government. In 1991 alone offshore platforms provided over $3 billion to the general fund of the U.S. Treasury, the Land and Water Conservation Fund, the National Historic Preservation Fund, and coastal states. Of this amount almost $1 billion went to the Land and Water Conservation Fund. This money is used to buy land for parks and recreation areas and aid in planning, acquiring and developing land and water areas for recreational use. The National Historic Preservation Fund received $150 million to identify and protect properties listed on the National Register of Historic Places.

With continued government support for exploration and production in the oceans, industry expects to continue producing these important revenues and energy sources to "fuel" the domestic economy for the long term. MMS believes that the OCS still contains significant amounts of oil and gas reserves. In 1991 they

reported proven reserves in the Gulf of 2 billion barrels of oil and 32 trillion cubic feet of natural gas. In addition, MMS estimates over 17 billion barrels of oil equivalent remain to be found in the Gulf of Mexico alone. This means that many fields are yet to be discovered and the deep water of the Gulf of Mexico can be the new frontier area for exploration and development in the United States.

MANAGING ENVIRONMENTAL AND SAFETY ISSUES

Management of safety and environmental impacts is an important factor to be considered when developing a research proposal involving an offshore facility. The interrelationship of the platform and the environment being measured is of concern. Will studies be biased by associated emissions and discharges or other by-products? Will workers need special protection or training to be safe on the platform? These are legitimate concerns—ones that we as operators and the MMS as resource protectors have spent considerable time and effort evaluating and controlling.

MMS is the lead regulatory agency responsible for safe and efficient OCS exploration and production. Along with the Coast Guard, Environmental Protection Agency, and a variety of state agencies, MMS has programs in place that address worker safety, natural resource protection, and conservation of mineral resources. Every aspect of industry's operations is strictly controlled through a complex structure of regulations and permits. This begins with stipulations included in leases and continues throughout drilling, facility construction and installation, production, and finally in the abandonment of nonproductive leases. Each phase of the operation must meet specific design and operating standards. The purpose here is to insure that operations are as safe as possible and that risk to personnel and environment is minimized. These tight safety and environmental standards are met through performance criteria and rigorous routine compliance inspections by both the regulators and operators.

INDUSTRY ENVIRONMENTAL STANDARDS

This attention to environmental and safety protection is critical. The Gulf of Mexico has one of the nation's most extensive barrier island systems and 2,574 km (1,600 miles) of shoreline. The adjacent wetlands and shoreline habitat provide critical breeding and feeding grounds for many species. In addition to supplying 25 percent of the nation's natural gas and 12 percent of its oil, the Gulf provides 40 percent of the total annual domestic harvest of commercial fish. Recreational users include millions of sport anglers and beach goers. The area is a major shipping center. In addition, population along the Gulf is ranked fourth regionally and continues to grow. Not only do the local uses and coastal populations impact the Gulf but also two-thirds of the land area of the United States drains into the Gulf through 33 major river systems (American Management Systems, Inc., 1991).

Since the Gulf is the quintessential multiple-use area, the oil industry as a user and beneficiary of the resources, exercises great care in preventing pollution. Drilling fluids, cuttings, and produced water make up the majority of waste from offshore operations. Water-based drilling fluids (primarily water and clay), well-cuttings, and produced waters (salty water that naturally occurs with the hydrocarbons and is extracted along with the oil) are discharged into offshore areas in accordance with the Federal Clean Water Act. Toxicity testing has been done on water-based drilling fluids since 1986 to establish that they meet acceptable levels prior to discharge. A toxicity test is being developed for produced water that will set similar limitations. It is the subject of much debate among modelers on how to best represent actual offshore dispersion associated with water depths and currents found in the oceans. At issue is how to best apply science to mimic real world systems. Once the modeling issues are resolved, produced water discharges will also meet strict toxicity limitations and demonstrate negligible impacts within meters of the platform.

With such strict water quality discharge limitations it should not be surprising that offshore platforms and surrounding waters are the basis for highly productive ecosystems. Scientists have determined that 20 to 50 times more fish can be found under and near oil platforms than in nearby soft bottom areas (Driessen p. 3, 1989). Platform legs are the perfect artificial reef environment for colonization by algae, barnacles, mussels, and anemones. It is believed that platforms assure an uninterrupted supply of nutrients as well as provide navigational reference points for fish and shelter from currents and predators. In addition to increasing the quantity of sea life, apparently platforms also have a positive impact on the quality. Government tests have consistently found much lower levels of oil, metals, and other pollutants in the mussels collected from platform legs than those taken from California's cleanest bays.

Platform power generation systems include natural gas fueled generators, turbines, and other combustion and fugitive emission sources. MMS is in the midst of a complex study to determine whether or not onshore non-attainment areas are significantly impacted by offshore development. The study will be completed in 1994. It will look at point sources and fugitive emissions in addition to associated transportation traffic. Results will be used to determine if further regulations are necessary should a significant impact be demonstrated. Direct measurements from BPX facilities demonstrated insignificant impact on onshore air quality. For example, daily levels of fugitive emissions from one of our largest platforms were less than would be emitted from the wet paint of a single new car.

OIL SPILL PREVENTION AND RESPONSE

The oil spill record of offshore platforms is remarkably good. Unfortunately the industry receives little recognition for this success. Less than 2 percent of oil in the oceans is attributed to spills from offshore drilling rigs and production platforms. The majority of oil in the oceans comes from tanker operations and from our cities. Domestic offshore platforms eliminate the need to transport oil long distances in tankers.

In 1991, only 636 barrels were spilled from 3,800 platforms in the Gulf of Mexico (Minerals Management Service, 1991). This excellent record results from the extensive training and careful planning of the exploration and production industry. Industry and the MMS believe that the best spill control technique is prevention. Personnel who work in areas where the potential for spills exists are trained to be aware and responsive. Comprehensive plans prepared by operators and annual training address not only who the response personnel are and where the equipment is located, but also how natural resources will best be protected.

POLLUTION PREVENTION

Pollution Prevention is perhaps the best approach to total environmental management. It is routinely practiced at BPX facilities. It makes sense to actively promote economically and technically sound waste reduction activities that protect the environment. As new technologies become economical they will open up a range of new options for offshore operations. Examples of these "next generation" technologies are becoming more common. One example being practiced by many offshore operators is subsurface injection. In this process oily cuttings are ground up and disposed of down the well bore, avoiding transportation to shore and landfill disposal. Bulk handling capabilities on new facilities is in its infancy. It has already resulted in reducing solid waste volumes and costs associated with product loss. One other example uses waste heat as an energy source. This cogeneration technique reduces fuel consumption and associated emissions while it eliminates the cost of another fuel source. While only cost effective on new structures, these examples represent improvements that are possible with emerging technologies and focused research.

PLATFORMS FOR RESEARCH: THE GULF OF MEXICO APPROACH

The National Oceanic and Atmospheric Administration (NOAA) is tasked with coordinating the many independent activities and operations, proposed or underway, that are collecting information on global change. Since the role of the oceans in buffering global climate change is not fully understood, NOAA has become very interested in the applicability of using offshore platforms for this research.

An existing program in the Gulf of Mexico, the Flower Gardens Ocean Research Project (FGORP), has hosted researchers on platforms for the past few years. This innovative program is coordinated through the Center for Coastal Studies, Corpus Christi State University. A steering committee including coastal state universities, MMS, NOAA, the Environmental Protection Agency, and industry reviews and oversees research proposals being considered for this program. Once selected, proposals are reviewed by the participating company to determine their feasibility. Once approved, the company provides the researchers access to its platform with the understanding that this project will not interfere with daily operations and will not compromise the safety of the personnel or the platform. BPX, recognizing the potential importance of climate issues, suggested that NOAA begin extending the FGORP concept worldwide. Since 1991, BPX has been working closely with NOAA and Woods Hole Oceanographic Institution to expand this concept and, early in 1993, offered to host research projects on our own platforms in the Gulf.

This approach to research provides a mechanism for a mutually beneficial relationship among academia, government, and industry that is not being forced by regulations. We anticipate that researchers will be anxious to conduct their studies from these safe and clean offshore structures and will obtain valuable scientific data that will help us all better understand the behavior of the ocean environment.

RESEARCH CONSIDERATIONS

Despite the seemingly convenient and protective environment of a self-contained platform, a researcher needs to understand that

there are many operational, logistical and individual facility constraints that must be designed into each offshore research project. Opportunities for research are not always available at every platform. Research possibilities will be limited by the operations planned at the location. The most likely opportunities for research at a given facility will be after drilling and nonroutine operations are completed and routine production is underway.

All facilities pay close attention to the safety of personnel, the environment and equipment. Accordingly all visitors are required to be aware of and comply with basic safety guidelines and rules in their daily activities. Safety training is provided to all visitors and is adapted according to the specific activities planned at a facility.

Equipment used in the research project must be adaptable and sturdy. Electrical power sources at the site will vary by facility process needs. Available power can range from primary batteries or solar cells at small unmanned sites to large turbine driven generators on major platforms. Research equipment will be subject to the wear and tear of a marine environment and must be designed accordingly. Since platforms produce highly flammable products, there is strict enforcement of rules regarding ignition sources and electrical area classification.

All personnel, equipment, and supplies are transported to a facility by either boat or helicopter. This logistical support is expensive and is optimized by keeping the number of trips to a minimum. With careful planning and scheduling, transportation can generally be made available to support research projects. Lead time to get equipment to the platform and availability of replacement parts and servicing must be built into all projects. In addition, flexibility must be designed into the schedule because there can be frequent delays and interruptions in transportation because of inclement weather and operational needs.

SUMMARY

Platforms are clean and safe facilities that provide invaluable opportunities for research while production is underway. They can be used effectively over the long term to expand the knowledge base of ocean environments and communities while providing valuable energy, jobs, and revenues to the local and national economies. As evidenced by other papers in this journal, the idea of using platforms to study the oceans is not new. What is new are the cooperative efforts to share resources, the potential for access into deeper waters, and the opportunity for industry to make a significant contribution to resolving environmental issues with sound science.

Environmental concerns affecting society are often complex, with many issues interrelated. Solving one perceived problem can often create another. Industry is concerned that rigid and prescriptive legislation can sometimes force inappropriate measures. Some "solutions" might be far too costly for the environmental gains or might cause results that were not intended. "Solutions" must always be based on sound science, assessment of risk, and proper balance between costs and benefits. To that end we want to be a player in addressing issues that involve the oceans.

There are heavy costs associated with failing to reduce serious environmental risks and of having insufficient information. As governments and industry continue to debate the political and economic merits of various options to address environmental concerns, it should always be remembered that "the facts" have dispelled more than one erroneous theory. We encourage industry, governments, and academia to find better ways of cooperating so these debates can be based on solid evidence rather than hypothesis.

ACKNOWLEDGMENTS

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REFERENCES

Driessen, P. K. 1989. Offshore Oil Platforms: Mini-Ecosystems, In: *Petroleum Structures as Artificial Reefs: A Compendium*, U.S. Dept. of the Interior, Minerals Management Service, Gulf of Mexico Region, New Orleans, LA.

Minerals Management Service. 1991. *Federal Offshore Statistics: 1991*, U.S. Dept. of the Interior, Minerals Management Service, Operations and Safety Management, Office of Statistics and Information, OCS Report MMS 92–0056. 163 pages.

American Management Systems, Inc. 1991. Marine Debris Action Plan for the Gulf of Mexico, Gulf of Mexico Program. 89 pages plus appendices.

Unique Opportunities of Oil Platforms for the Study of Sediment Transport and Accumulation

COMMENTARY

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INTRODUCTION

The continental-shelf environment represents an important portion of the world ocean. Many valuable living and non-living resources are associated with its waters and underlying seabed. The shelf is also the portion of the ocean located closest to the world's human population. Therefore, we need to maintain the quality of shelf seas while we exploit their resources.

Solid particles are extremely important constituents within fundamental oceanographic processes operating on continental shelves. These particles include sand, silt, and clay supplied by rivers, glacial ice, and winds. Biological processes also produce particulate material, such as shells of organisms, carbon from dead flora and fauna, and fecal matter. Many types of dissolved constituents from seawater (e.g., radioisotopes, heavy metals, pesticides) are adsorbed to the surfaces of organic and inorganic particles. The oceanographic processes that control the transport and accumulation of particles on continental shelves determine the fates of the particles as well as the associated materials.

Much of the geological record of Earth history is locked within sedimentary rocks formed in ancient continental-shelf settings. A basic understanding of how shelf processes move particles and emplace them to form sedimentary deposits will allow us to interpret ancient rocks better. Many of these rocks contain valuable mineral and oil reserves, and therefore the studies have both a basic and applied relevance.

Unfortunately continental shelves are very complex and very energetic realms, because they are influenced by mechanisms characterizing both terrestrial areas (e.g., river floods) and oceanic areas (e.g., astronomical tides, surface gravity waves, western boundary currents). The complexity means that data must be collected with good spatial and temporal coverage. The energetics mean that typical platforms for these observations (ships) are difficult to use during periods of high-energy conditions (e.g., storms), when the most important sedimentary processes occur.

The objective of this commentary is to discuss: (a) the scientific needs for continental-shelf studies of sediment transport and accumulation as particularly relevant to oil platforms; (b) the unique characteristics of these platforms for performing research; and (c) some of the potential limitations associated with platforms.

STUDIES OF SEDIMENT TRANSPORT AND ACCUMULATION

The 1990s promise to be a period of intense investigation of the coastal ocean, and many of the studies will examine the transfer of particulate material through continental shelves. The following is a general list of considerations relevant to future studies. Most of the ideas presented below are discussed in more detail within Brink et al. (1992) and Nittrouer and Wright (1993). Although the focus is upon future studies, the insights are derived from past research.

Sea-Surface Processes

The surface of the ocean is the origin of many relevant considerations for sediment transport. Winds deform the sea surface, creating the surface gravity waves that are responsible for large stresses on ships, platforms, and the seabed. Winds also impart a shelf-wide slope to the water surface, by piling water against or pulling water away from the coastline. This surface slope leads to bottom currents, which are coupled with the effects of waves to erode and transport particles from the seabed.

Energetic Events

The mass transport of particles is proportional to some high power of bottom-water velocity. Therefore, energetic events have a disproportionate effect on the erosion, transport, and redeposition of particles. These events are usually storms (tropical or extratropical) but could be large-swell conditions with superimposed local currents.

Particle Sources

Most sediment movement on shelves involves the rearrangement of material supplied earlier. However, the input of new material has great relevance to understanding the origin and alteration of particles. Among the potential supply mechanisms are river plumes, glacial ice, biological productivity, and aeolian transport.

Bottom Boundary Layer

The preponderance of sediment transport within the ocean occurs within the lower few meters of the seabed. This is a region

referred to as the bottom boundary layer. Current- and wave-induced water velocities go to zero near the surface of the seabed. The shape of the velocity profile influences and is influenced by the seabed and controls sediment transport. The characteristics of the boundary layer fluctuate over many time scales.

Reworked Layer in the Seabed

Physical-oceanographic processes and activity of benthic biological organisms (e.g., feeding, locomotion) rework the upper ten or so centimeters of the seabed. These processes determine which particles are buried at a location and which particles are kept near the seabed surface within reach of erosional events (allowing transport to other locations). These same processes determine the aggregate characteristics (sedimentary structure) of the buried sediments, and thus control the "fingerprint" used to recognize environmental characteristics in ancient marine rocks.

UNIQUE CHARACTERISTICS OF OIL PLATFORMS

Platforms have potential application to many types of coastal oceanographic research. The aspects of platforms described below are particularly useful for studies of sediment transport and accumulation. The studies traditionally involve sampling and measurement from ships (coring, chlorinity-temperature-depth or CTD casts) or monitoring at a fixed site (e.g., current-meter and sediment-trap moorings).

Exact Positioning

Even now, in the days of global positioning systems and fixed transponders, some places at some times are difficult to locate or reoccupy exactly. This can be due to equipment failures or foul weather. In any case, finding a site in the ocean still presents difficulties. However, there is no ambiguity associated with the location of a study site near an oil platform, whether the site is at the platform or a fixed distance and direction away from the platform. For study of seafloor micromorphologic changes (e.g., physical bedforms and benthic biological features) repositioning accuracy is needed on the order of 1 cm, and platforms are ideal.

Permanent Structure

The lifetime of a platform is effectively permanent compared to most types of oceanographic moorings. This is important because many of the processes controlling sediment transport and accumulation require long-term observations. Some processes operate with a cyclical nature and require time-series data to identify their characteristics. Other processes are stochastic, and long-term observations are needed to record their occurrence. Typical oceanographic moorings are in place only for periods of months (a year at the longest). Recovery and redeployment are difficult and expensive. A mechanism for easily maintaining instruments on or near an oil platform would greatly facilitate long-term measurements.

Minimum Chance for Research Losses

Many instruments deployed on continental shelves are lost due to fishing activities. Pristine seabed sites for sediment studies can be destroyed by dragged anchors or trawling. Locations marked by surface buoys often attract rather than divert activities that destroy research studies. From the other perspective, a net torn by oceanographic gear is not appreciated by fishermen. Oil platforms are large enough structures that most marine activities will give them berth, thus protecting experiments in the vicinity of the platforms.

Stable During Energetic Events

As described previously, periods of extreme winds, waves, and currents (usually during storms) are the times of maximum sediment response. Many types of sampling in the water column (e.g., profiles of suspended sediment) and seabed (e.g., observations of sedimentary structure) should be done during or immediately after these events. Unfortunately rough sea conditions trap ships in ports and/or prevent work on board ships. Oil platforms are stable, and work from them is possible during sea conditions that are totally unsuitable for work from ships. During energetic events, many fixed instruments should have their rates of data acquisition accelerated, but there is no easy mechanism for a person to adjust data collection. Instrument systems could be controlled directly from inhabited platforms or the systems could be controlled indirectly by telemetry on uninhabited platforms. In fact, it is now feasible to effect such telemetry by inexpensive cellular telephones.

Structure for Equipment and People

Platforms are fixed structures on (or near) which instruments can be mounted and from which water/sediment sampling can be accomplished (Figure 1). Meteorological instrumentation can be mounted above the water level. Within the water column, current-meter arrays can monitor profiles of velocity near the seabed and acoustic-Doppler current profilers can monitor the remainder of the water column. Optical instrumentation can be distributed throughout the water column to measure suspended-sediment content. Rotating side-scan

sonar systems can be mounted on the legs of platforms to monitor micromorphology of the surrounding seabed surface. Cranes and winches on board platforms can be adapted for use of seawater samplers, hydrographic probes, and seabed coring devices. With exact positioning possible, sophisticated tracer studies (i.e., with marked particles) can be undertaken. In general, oil platforms can provide the potential for many studies that would be impossible with present ships or anchored moorings.

POTENTIAL LIMITATIONS OF OIL PLATFORMS

In addition to a range of administrative, bureaucratic, and logistical difficulties (e.g., permission, liability, access), oil platforms present some real scientific limitations for research studies.

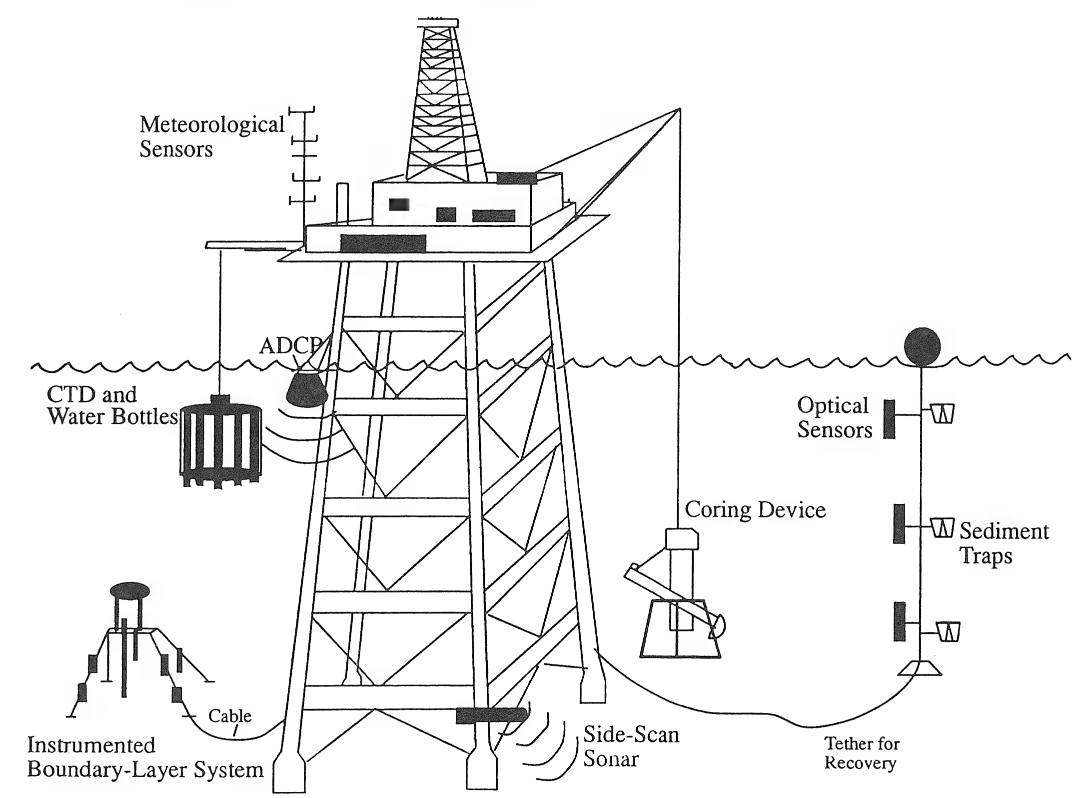
Alteration of Flow

The structures represent an impedance to flow of seawater. Streamlines within some proximity to the platform will be deformed, leading to a modification of the sediment-transport field and creating areas of increased bottom shear stresses (sediment scour) and decreased shear stresses (sediment deposition). The degree of effect will depend on the exact design of each platform, ambient physical-oceanographic conditions, and the observation of interest. Adjustments can be made by working on the upstream or upwind sides of a platform if a particular flow condition (e.g., storm current) is relatively predictable. In some cases, observations can be made near a platform, but beyond the region of significant flow deformation. Extended booms can help to reduce proximity of instruments to the platform.

Modification of Substrate

The usefulness of an oil platform for studies of sediment transport and accumulation would be reduced if the seafloor were unnaturally disturbed. Bottom character could be affected by debris released from the platform or by bedforms modified by flow deformation (described above). The roughness of the seabed has a major influence on sediment transport. An unnatural seafloor also would influence the relevance of studies investigating the formation of sedimentary

FIGURE 1. A schematic representation for use of an oil platform for studies of sediment transport and accumulation. Meteorological instruments can monitor conditions above the seawater surface. Current meters (ADCP = acoustic-Doppler current profiler), pressure gauges, and optical instrumentation can document sediment-transport considerations. A sidescan sonar system can record information about micromorphology of the seafloor. Water samples, sediment samples, and hydrographic data (CTD = chlorinity-temperature-depth probe) can be collected from the platform.



strata below the sediment-water interface. Related considerations include alterations to benthic habitation, such as a community of benthos significantly different than in the ambient seabed surrounding the platform. Again the best solution would be to identify study sites some distance beyond the platform but still close enough to take advantage of it.

Limited Spatial Coverage

Observations at a platform represent one particular location in the ocean. When dealing with processes as dynamic as the transport and accumulation of sediment, this could be a severe limitation for resolving active processes. However, regarding spatial coverage, observations associated with an individual platform are no worse than those with solitary water-column moorings or solitary bottom-instrument deployments that typify most studies now. The strength of studies from oil platforms is in the realm of understanding temporal variability. In addition, some shelves around the world have dense distributions of oil platforms, sufficient to evaluate spatial as well as temporal differences in sediment transport and accumulation.

CONCLUSION

During the next decade extensive studies of the coastal ocean will be undertaken. Oil platforms have potential attributes that would be very beneficial for future studies of sediment transport and accumulation. Platforms also have intrinsic limitations, but their potential benefits justify more detailed consideration of platform use (assuming that access is a real possibility).

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REFERENCES

Brink, K.H., Bane, J.M., Church, T.M., et al. 1992. Coastal Ocean Processes: A Science Prospectus. Woods Hole Oceanographic Institution, Tech. Rept. WH01-92-18, 88 pp.

Nittrouer, C.A. and Wright, L.D. 1993. Transport of particles across continental shelves. *Rev. Geophys.*, 31.

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The Geosat Committee has been working with the U.S. Committee on Earth and Environmental Sciences (CEES), first under Dallas Peck (U.S.G.S.) and subsequently under Fred Bernthal (NSF), the current Director of CEES. The industry interface body for facilitating industry coordination and communication with the Federal agencies that compose the CEES is the Private Enterprise Government Interface (PEGI). PEGI was created in 1992 and presently operates under its Director, Bill Busch, NOAA Office of Global Change.

PEGI is working with GOSAP participants, British Petroleum, Woods Hole Oceanographic Institution, Texas A&M, and others to develop industry-government cooperation in the use of industry offshore platforms for cooperative research. PEGI approached the Geosat Committee, which has agreed to utilize the GOSAP project in the Gulf of Mexico to encourage industry to broaden the use of offshore platforms for further cooperative research on a worldwide basis where mutually feasible. This effort will encourage industry participation with NOAA and other government agencies to employ offshore oil platforms world-wide as an active part of the ocean, air and satellite date collection program under the Global Ocean Observing System (GOOS) being proposed by NOAA and the U.S. Navy.

PROJECT GOSAP

The Gulf Offshore Satellite Applications Project (GOSAP) is a multi-organizational effort to determine how best to use remote sensing technology to address offshore problems and operations faced by the exploration and marine engineering industries. Remotely sensed data integrated with "sea truth" are used to quantify meteorologic and oceanographic events, to detect and track ocean currents and gyres, to image the sea floor, map subsurface geology, or detect oil seeps from orbital altitudes.

In fall 1992 and spring 1993 the European Space Agency (ESA) acquired synthetic aperture radar (SAR) imagery for GOSAP from the European Remote Sensing Satellite (ERS-1) satellite over the Santa Barbara and Gulf of Mexico test sites. In coordination with the Gulf of Mexico overflights, a very comprehensive program of sea truth was conducted by various agencies, ranging from sea bottom submarine observations, sea surface sampling from ships and platforms, aircraft overflights, and imagery from several satellites. An airborne laser fluorescence survey will be conducted in the area shortly after the ERS-1 overflights.

Initial processing of the SAR, Landsat, and Satellite Pour l'Observation de la Terre (SPOT) data by GOSAP members has resulted in excellent images of surface oil slicks in both the Santa Barbara and Gulf of Mexico sites. Progress is being made in correlating sea, air, and spaceborne measurements to determine optimum procedures for detecting and monitoring oil in marine environments.

GOALS

Project GOSAP is being undertaken under the auspices of the Geosat Committee by members of the petroleum, marine, and environmental industries representing about 30 companies, government agencies, and universities. GOSAP participants are evaluating the potential for satellite-based offshore exploration, ocean engineering, and environmental applications using combined satellite and airborne measurements constrained by real time "sea truth."

Participants are comparing sea surface spectra from satellites (ERS-1, Radarsat, shuttle imaging radar or SIR, Seasat, Landsat, SPOT, and others) with water column, sea surface, and sea floor measurements from instrumented fixed and mobile platforms in the Gulf of Mexico. These comparisons will yield methods aimed at establishing repeatable correlations between sea surface, sea floor, subsurface, and general geology. Techniques developed to process the data sets will be applied to exploration, engineering, and environmental problems encountered by Geosat member companies.

Data are being evaluated over two test sites: the Santa Barbara area offshore southern California and the Gulf of Mexico. Both sites contain a number of known active oil seeps (see Figures 1 and 2), have extensive existing marine gravity surveys, and contain numerous instrumented offshore platforms. Extensive measurements are being made above, at, and below the sea surface.

The potential correlation of satellite-collected sea surface signatures, oil seeps, subsurface and general geology will enable explorers to extrapolate these techniques into less fully understood test sites and eventually into unexplored frontier areas worldwide. Petroleum exploration in little known regions requires synoptic wide area coverage both onshore and offshore. While onshore petroleum exploration

FIGURE 1. ERS-1 synthetic aperture radar image of oil slicks in the Santa Barbara Channel, California. Oil slicks and ship wakes are visible in the image north of Santa Cruz Island. (Copyright ESA, 1993. Produced by CCRS. Image processing courtesy of Pecten International.)

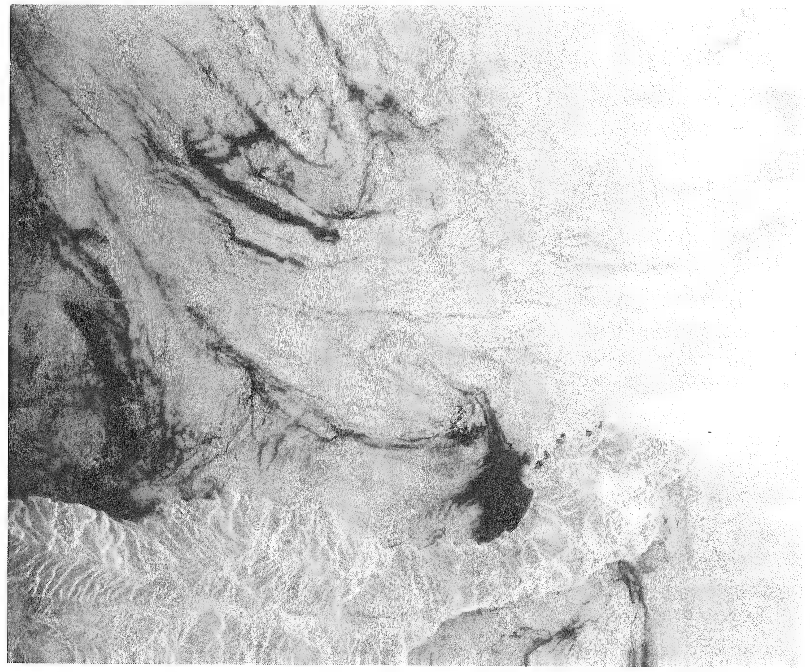
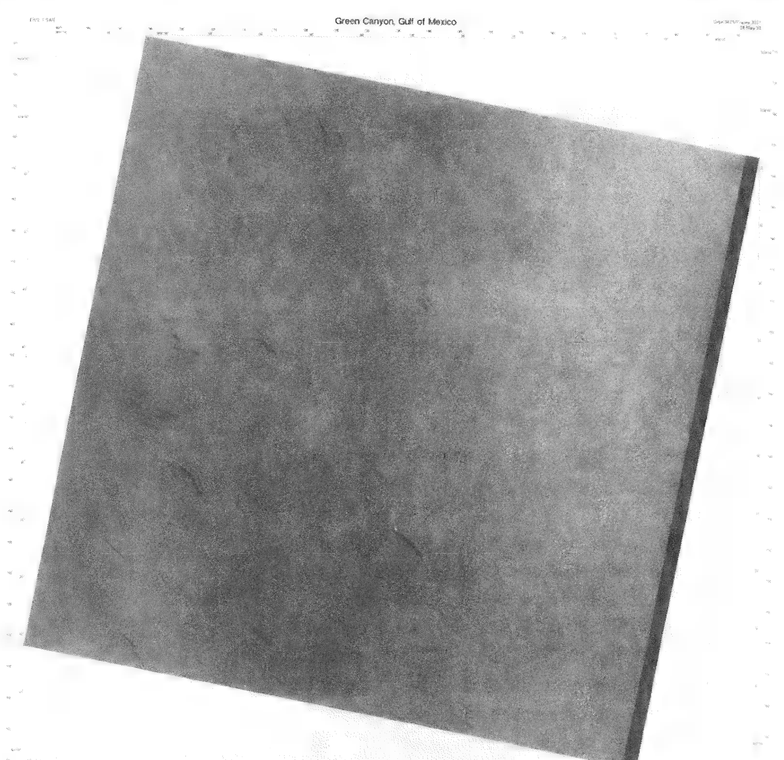


FIGURE 2. ERS-1 synthetic aperture radar image of oil slicks in the Green Canyon Area of the Gulf of Mexico. (Copyright ESA, 1993. Produced by CCRS. Image processing courtesy of Earth Satellite Corporation.)



using remote sensing techniques has become nearly routine, many of the remaining oil provinces within reach of present drilling technology lie offshore at shallow to moderate water depths; thus it is useful to develop remote sensing methods which extend land-based interpretations into the shallow offshore.

The use of satellites to obtain area wide meteorological and oceanographic data will enable industry to have a more complete picture of oceanographic events that are occurring at or near an area of activity. Non-satellite techniques provide only sparse "snapshot" data of these events.

ACTIVITIES

The GOSAP project involves cooperation between organizations who each contribute to the data collection, image processing, interpretation, and report writing phases. Most participating organizations have several people assigned to one or more of the five GOSAP working groups discussed below.

Sea-Truth Activities

In conjunction with acquisition of the ERS-1 satellite data over the Gulf of Mexico test site, GOSAP is fielding several teams to collect simultaneous sea-truth data (Table 1). The goal of one particular set of observations is to verify the presence of slicks detected in the satellite imagery in a water depth range of 750 to 1,000 meters, a previously undocumented regime. Because seep activity is sporadic in time, we performed near real-time interpretation of the ERS-1 imagery to locate active seeps (Figure 2) and to direct a special deep-diving submarine to visit the most active seep sites and pinpoint seepage locations on the seafloor. We worked closely with ESA officials, the ERS-1 Order Desk, the Canadian Centre for Remote Sensing, Radarsat International, and GOSAP participants to achieve a quick release of ERS-1 imagery. Earthsat analyzed the satellite images, located the slick sources, and directed the submarine to the seep sources.

TABLE 1. Sea-truth data being collected by GOSAP teams in conjunction with acquisitions of the ERS-1 satellite data over the Gulf of Mexico test site.

ERS-1 SAR Imagery	Instrumented Buoys
ERS-1 Altimetry Data	European Space Agency
ERS-1 Scatterometer Data	SPOT Image Corp.
SPOT Imagery	processed by Earthsat
Landsat Imagery	Texas A&M (GERG)
Submarine NR-1	MSRC
NASA ER-2 (U-2) Aircraft	World Geoscience
ALF Survey	LATEX / USM / SAIC
AVHRR + Aerial Photography	Office Naval Research
High Altitude Remote Sensing	Shell
Instrumented Oil Rigs	Marathon

In early June, an ER-2 will overfly portions of the continental slope between the 500 and 2,000 m isobaths collecting imagery on two flight patterns: a four-spoked star pattern centered on the sun-glint when the sun-glint is in the vicinity of Green Canyon 234/371 and along isobath (East-West) flight-lines between the Green Canyon (GC) and Garden Banks (GB) lease areas. The ER-2 will be equipped with a down-looking Daedalus Airborne Ocean Color Imager (AOCI) and a forward-looking electronic still camera with multiple polarizing filters. The goals of this exercise are to provide additional imagery of slicks from different sensor types and to further document the characteristics of surface slicks formed by natural seepage. The AOCI will provide information on the primary productivity in the vicinity of the slicks; the polarizing camera will produce high-resolution images of the slicks that will provide information on the heterogeneity of slick thickness.

High quality aerial photographs will be acquired from an aircraft underflying the ERS-1 over areas of known coastal bathymetry, an eddy, and storm fronts. These data will be used to test methodologies and technologies to observe and follow energetic ocean features such as fronts and eddies, to use ocean wave refractions to determine coastal bathymetry and energetic fronts, and to determine the effects of weather and sea-surface conditions on the SAR imagery.

Gravity

Satellite altimeter data yield the possibility of direct determination of the ocean surface, i.e., the height of the instantaneous sea surface above a reference ellipsoid. For geodetic purposes the analyses of altimeter data provides information about the shape of the mean sea surface, normally called the geoid, from which geopotential or gravity information can be derived.

In ocean areas where water depth information is sparse, a number of studies of altimeter data have identified hitherto unknown seamounts, fracture zones, and subduction zones. In offshore areas where reliable water depth information is separately available, elimination of the sea bottom topography yields geopotential maps or gravity maps giving information about significant density contrasts within the earth's crust and sedimentary column.

GOSAP investigators are producing a number of geopotential and/or gravity maps over the Gulf of Mexico and the Santa Barbara test areas from altimeter data and will evaluate derived gravity maps with existing shipborne gravity measurements, correlate and demonstrate the ability of remote sensing in exploration by detecting geologic and geophysical anomalies over areas where extensive seismic surveying and drilling have provided adequate geologic control, and explore methods for characterizing major structural features (e.g., sedimentary basin, salt domes, structural highs).

Several GOSAP participants have been actively investigating the issues of processing satellite altimetry to derive an estimate of the marine gravity field and then to measure the accuracy and resolution of the gravity data. Several members have been developing procedures and comparing existing satellite gravity with shipborne gravity. Petroscan has published a comparison of the resolution of several satellite gravity determinations and estimated the improvement when the ERS-1 data will be added.

The Analytical Sciences Corporation (TASC) has used the 1-sec average sea surface heights from the 3-day ERS-1 repeat cycle to compute mean height profiles and to evaluate the noise levels and gravity field resolution capability of the ERS-1 altimeter data. Preliminary results indicate that the performance of ERS-1 is comparable to that of the Geosat altimeter. Deflections of the vertical should be recoverable (for wavelengths longer than about 35 km) to an accuracy of about 1 arcsecond, except near land. Since the quality of the 1-sec average sea surface heights provided in the data is highly variable, it is necessary to work with the 10 sample/sec heights and to carefully edit these to obtain the best possible profiles (20 sample/sec data would be even better). It is expected that careful data processing, along with averaging of at least 20 repeat tracks, should reduce the errors in recovered gravity anomalies to the level of about 3 or 4 mgal.

Oil Slick Monitoring

The ability to detect both natural or man-made oil slicks in coastal waters by spaceborne synthetic aperture radars (SAR) has been demonstrated in the Seasat and shuttle imaging radar (SIR A & B) programs. Several data passes over the test site reveal the persistent or ephemeral nature of the slicks, suggesting a natural or man-made origin (long-term seep versus oil spill or pipeline leak).

As an exploration tool, the remote identification of hydrocarbon seeps is particularly useful to geologists responsible for large or frontier regions. General models that describe seepage from source to surface must consider mechanisms for migration, geometry and density of migration channels (faults, fractures, preferential directions of porosity and permeability), barriers to migration, either physical or chemical (oxidation/reduction barriers), and ultimate expulsion at the sea floor or land surface, followed by degradation or dispersion.

GOSAP investigators are attempting to determine optimum parameters for detection of oil slicks (e.g., spectral bands, image processing techniques, data synergism, volume and film thickness of oil) and to discriminate between natural and man-made slicks temporally, spatially, and/or spectrally. Earth Satellite Corporation has processed a suite of satellite imagery of oil seeps in the Santa Barbara Channel to determine best parameters to detect oil in the marine environment. Seeps enhancement work has been done on spills in the Arabian Gulf (AVHRR, TM) and Santa Barbara Channel (MSS, TM, ALMAZ preliminary).

A SPOT XS image of a major oil slick in the Gulf of Mexico from the tanker *Mega Borg* was processed by Amoco's Remote Sensing Group to develop operational image processing techniques. Additional work is ongoing in the Middle East (Landsat TM) and the Santa Barbara Channel (TM, MSS).

Remote detection of natural seepage can be used to extend the probable range of chemosynthetic communities dependent on hydrocarbon seepage in the Gulf of Mexico. Conversely, presence of the communities documents that natural seepage is ongoing in a particular location and that it has persisted recently. The goal of the seafloor observations is to document a previously undocumented seep feature based on remotely sensed slicks. Accomplishing this will demonstrate that natural oil seepage is current and ongoing at the site and will provide specimens and observations from communities at intermediate depths. Based on thematic mapper imagery and on photographs taken from the space shuttle, communities in the 900 m depth range are believed to be located in GC321 and GC287. These sites have not previously been explored by submarine although chemosynthetic fauna were recovered by trawling in GC278.

Current Monitoring

The Gulf of Mexico has unique current regimes: the Loop Current and eddies that spin off from the Loop Current. Precise definition of spatial extent and current magnitudes of eddies is lacking. Satellites have the potential to resolve these issues. Present monitoring techniques include: infrared satellite data limited by cloud cover and seasonal water surface temperature differences, deployment of current measurement devices, shipboard acoustic-Doppler current profiler (ADCPs), and underwater cables.

GOSAP participants are determining if eddy current regimes can be properly defined in real time and on a cost-effective basis. They are currently developing a method to disseminate data products.

Expendable bathythermograph (XBT) measurements were made on several cruises at approximately 10 nm spacing. A number of current measurement were also made using ADCPs and expendable current profilers (XCPs). The measurements showed that Eddy Triton was only separated from the Loop Current during the second cruise. On the other two cruises a connection between the two features existed at the southeastern corner of the cruise track. On all the cruises, an anticyclonic center of circulation existed near the center of the cruise track. Dynamic heights have been calculated for each of the XBT profiles using a standard temperature-salinity curve for Loop Current water. The relief at the center of circulation is on the order of 0.65 m.

Wind and Wave Measurements

Several Gulf of Mexico oil platforms are instrumented with wind and wave measurement devices that transmit routinely to the National Weather Service; these data are combined with the wind and wave data collected from the National Weather Service buoys deployed in the Gulf. Verification that satellite data can quantify wind and wave data will lead to improved weather forecasting and provide an enhanced database which could lead to improved structure design criteria.

Database and Archive

The diverse computing environments spread throughout North America of the companies, universities, and government organizations participating in GOSAP creates a unique set of problems for data distribution, sharing, and archiving. In addition to ERS-1 data products, GOSAP members are contributing and sharing other data, such as satellite imagery, gravity data, weather information, well logs, bathymetry, and oceanographic data. These and other data are being archived and distributed by the Database and Archive group. This group is also implementing an electronic catalog (index) for all the GOSAP data products that can be browsed by GOSAP members.

SUMMARY

Members of Project GOSAP are undertaking a comprehensive data collection program in the Gulf of Mexico to evaluate commercial and scientific applications of satellite data in the areas of ocean engineering, offshore exploration, and environmental applications. Instrumented offshore oil platforms provide a stable, valuable source of data for calibrating airborne and satellite remotely sensed data. Improved understanding of these new technologies with enhanced image processing and analysis techniques is stimulating additional research within the participating organizations.

COMMENTARY

Environmental Research As It Relates to Offshore Oil Exploration and Production

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INTRODUCTION

Norway has been a major oil producer since 1971. The discoveries of Ekofisk, the largest field in Europe at that time, its neighboring fields, and Frigg brought optimism to the industry and led to increased exploration. More recently, these offshore installations have invited exploration of their unique abilities to make long-term time series of both atmosphere and ocean parameters at regular intervals in fixed positions.

Most of the production platforms are designed for operation over several decades. The capability of making homogenous, consistent, and synoptic data sets from the ocean-atmosphere system has always been difficult using traditional "platforms" such as ships or buoys. The possibilities provided by "permanent" platforms to conduct regular measurements at the same location are of great importance for monitoring and forecasting environmental conditions.

The environmental investigations performed today in connection with offshore exploration and production vary in a field development project, from the exploration to the production phases. It is stressed that the activities mentioned here are those being examined by Norsk Hydro and may vary from one company to another.

ENVIRONMENTAL INVESTIGATIONS

It is convenient to divide the environmental investigations into phases reflecting the activities before the start of production and after. Prior to production drilling operations and field development, environmental studies are required to provide reliable input data from the region considered. Some examples are as follows: design and construction calculations, mooring layouts, fatigue and design life calculations, planning and marine operation procedures, and consequence and risk analyses.

The need for data is covered through existing databases, simulation models and, if needed, by collecting new data sets. The oil companies operating on the Norwegian continental shelf have initiated development of several databases (e.g., for winds, waves, currents, ice conditions, and vulnerable resources). These databases are vital for a number of investigations in the preproduction phase.

Central to consequence and risk analyses are studies of the potential effects of planned as well as possible uncontrolled discharges to the sea. The most immediate uncontrolled discharge may be a blowout during which a substantial amount of oil may enter the sea and cause damages to biological resources. Examples of planned emissions are produced water, draining water, and drill cuttings. These emissions may contain different chemical constituents including given concentrations of hydrocarbons. The individual events, such as blowouts, oil leakages, dispersion, and oildrift, are identified and examined with respect to position, depth, and strength. From prescribed initial and boundary conditions, a system of models is applied to identify potential ocean and coastal areas that may be affected. This is important for giving estimates of possible damages to vulnerable resources. For instance, in the simulation of an oil blowout, one needs to know the shortest drift time, the possible location, and the amount of oil. These simulations are based upon long time-series of winds together with climatological flow fields and are of great importance for designing a reliable contingency plan.

In the production phase, the environmental studies are more focused on monitoring oceanographic and meteorological parameters and accounting for discharges and their effects. Long-term data sets are important in case of a need for reassessment of earlier calculations and for further research. A number of parameters are observed on a regular basis with intervals from a few hours to several years. Yearly, a marine survey is conducted where a comprehensive physical and chemical observation program is carried out in a fixed network. Every third year the survey is extended to include biological parameters with emphasis on the benthic boundary layer.

EMISSIONS AND DISCHARGES

The main task of an environmental accounting system is to provide data on all important emissions and discharges such as carbon dioxide (CO_2), nitrous oxides (NO_x), and other greenhouse gases. In addition, the oil content in produced and drained water, oil spills, all chemicals used and discharged during drilling and

production, and the special waste taken ashore are accounted for. A computer-based system is used to record all incoming parameters, such as oil and gas, and to estimate all emissions and discharges.

The artist's rendering of a production platform (see front inside cover of this issue) provides an overview of potential emission sources. The sources are identified numerically and represent the following:

1. *Carbon dioxide (CO_2)* is formed by the combustion of gas in the turbines to provide energy for the production and transportation of oil and gas and for the drilling of wells. Some gas is also flared as part of normal operational safety measures. Diesel power is used for power generation on drilling rigs. Emissions of CO_2 from Norwegian oil and gas activities constitute 20 percent of total national emissions. For comparison, the contribution from private automobiles is 16 percent.
2. *Nitrous oxides (NO_x)* are formed at high temperatures through reactions between nitrogen and oxygen in the air. Power generation is the dominant source. Emissions from offshore activities cause 13 percent of Norway's total emissions. Actions to reduce CO_2 also reduce NO_x. Norway has committed itself to reducing NO_x emissions by 30 percent from 1986 to 1998.
3. *Volatile hydrocarbons (VOC)*, with the exception of methane, when combined with NO_x, can produce ozone or similar components at ground level, which may cause health problems or damage vegetation. VOC emissions are largely a result of tank venting during oil loading offshore or at the land terminals. VOC emissions will most likely diminish as a result of reduced volume of offshore oil loading. Industry is evaluating the possibilities to reduce the emissions at terminals.
4. *Methane (CH_4)* releases from the oil industry are modest compared to other sources. Oil loading and gas leakage from production, transportation, and storage result in the greatest emissions of methane from the oil industry.
5. *Halon* is a synthetic gas used as a fire extinguisher. The most important environmental impact of the gas is its effect to reduce the amount of ozone at high altitude. The use of Halon will be discontinued before 1995.
6. *Produced water* is water from the reservoir produced together with oil. The water is separated from the oil and treated before it is released to the sea. Produced water contains traces of oil and process chemicals. The releases of produced water contributed 45 percent of the total release of oil from the Norwegian oil industry in 1992. The produced water is rapidly diluted after it is released, but the sea around the installation will still contain traces of dissolved oil. Work is ongoing to reduce the releases through improved treatment technology or by re-injection of produced water in the reservoir.
7. *Water-based or oil-based drilling mud* are required for the drilling of wells. The mud contains various chemicals that may have adverse environmental effects. The drilling mud is recovered and reused. When the mud is no longer suited for use, the oil-based mud is brought ashore for treatment while the water-based is released to the sea. Oil contaminated drill cuttings are brought onshore for treatment, while other cuttings are dumped in the sea from the drilling installation. Industry is working actively to reduce the use of oil-based mud.
8. *Methods for milling the drill cuttings* and for *re-injecting them* in the geological formation from which they came are being examined.
9. *Drain water* from the platforms, consisting of rain-water and other sources, is collected through the open drain system. The oil content in this release is less than 1 percent of the total oil release on the Norwegian Continental Shelf. Prior to the release of the drain water the potential oil content is limited by separating the various sources that may become contaminated with oil and by treating them in an isolated system.
10. *Ballast water with traces of oil* is released in connection with offshore loading and oil loading at the land terminal. Ballast water from older tankers without separate ballast tanks will contain traces of oil from the previous oil cargo. This water is cleaned in the terminal treatment plant before it is released to the sea. Regular surveillance of the conditions in areas outside the terminal have shown that these releases have had no adverse environmental effect.
11. *Cooling water* and *wastewater* are other types of releases but their environmental effect offshore is insignificant.
12. *Oil spills* from exploration drilling and production facilities may occur as a result of technical failure or operational errors. In 1991, oil spills represented 28 percent of total release from the Norwegian oil activity, however, most spills were small. Large spills that create oil slicks represent a hazard to birds and seals and may contaminate shore lines. Oil spills are prevented by good equipment, preventative maintenance, and good operational routines.

SUMMARY

With the further expansion of oil and gas fields in the North Sea, the discovery of fields in the arctic seas, and the extension of platforms to greater depths off the continental shelf areas, tremendous opportunities exist for conducting oceanographic and atmospheric research. This capability has heretofore been nonexistent. It also provides a need for governments, science communities, and industries to work closely together in addressing environmental issues. Industry is dedicated to a very active role in ensuring that platform-related environmental concerns are addressed and that any adverse impacts are eliminated or minimized.

Aquaculture and the Environment
by T. V. R. Pillay
John Wiley & Sons, Inc. (1992)
New York. 189 pages. $59.95.

Reviewed by
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Pillay's *Aquaculture and the Environment* is a timely book focusing primarily on the impact of aquaculture on the outside environment. There are fourteen chapters with an extensive reference section, which allows the reader to pursue selected subjects in more depth. The chapters are well chosen to cover the principal areas of concern relative to aquaculture's impact on the environment. There is some treatment on the effect of the environment on aquaculture and the importance of water quality to successful aquaculture. The chapters provide enough detail to be useful to the experienced aquaculturist but the style is clear enough to provide the novice with a good introduction to the topic.

The first four chapters set the stage for the rest of the book by describing general measures of water quality and the nature of environmental impacts that are encountered in areas where aquaculture is practiced. Several different aquaculture systems are characterized in terms of their effluents and general effects on the environment. Land-based systems are compared with systems established in coastal areas and the concepts of hydrodynamics, effluent discharges, hypernutrification, eutrophication, chemical pollution, and exotic species are introduced. Chapter 4 presents a brief description of observed environmental impacts in different areas of the world.

Chapter 5 provides an in-depth review of the criteria for siting and design of aquaculture farms. Useful data include U.S. Environmental Protection Agency effluent discharge requirements, guidelines for choosing an aquaculture site, farm density guidelines, considerations for siting aquaculture facilities on marshes and mangrove areas, and farm designs for proper water exchange and waste treatment. The concept of providing additional water treatment to effluent is introduced with descriptions of settling ponds and different filtering mechanisms. Examples of efficiencies of different waste removal systems being used in different countries provide the reader with a good idea of cost and complexity of waste treatment.

Aquaculture systems can make use of waste products from other industries and human activities. Chapter 6 describes the use of animal wastes, domestic sewage, waste heat from heavy industry, and electrical generation in aquaculture. The concept of water reuse is presented as an ideal that has not yet been reached, except for the most highly valued aquaculture products.

Chapter 7 provides extensive information on the sources and processes of waste production in aquaculture. Several different types of waste, including unconsumed feeds, feces and other metabolic wastes, fertilizers, chemicals and drugs, are discussed.

Easy to use tables are provided to help the reader understand the qualities and quantities of different waste materials. Chapter 8 provides a brief treatment of the importance of quantity and frequency of waste discharge relative to the carrying capacity of the environment.

Chapters 9 through 12 provide an excellent treatment of the implications of using exotic species in aquaculture, the possibility of introducing pathogens to the environment, the impact of aquaculture on bird and mammal populations, and the actual and perceived safety of aquacultural products. These topics all impact the socio-cultural and economic aspects of aquaculture, the focus of chapter 13, and form the basis for most of the public and governmental opposition to aquaculture. Chapter 9 provides the protocol suggested by the American Fisheries Society for introduction of exotics as well as the code of practice adopted by the International Council for the Exploration of the Sea for introduction of exotic species. Chapter 10 provides a brief description of the possible involvement of aquaculture as a vector for disease transfer to commercial species in the natural environment. Chapter 11 describes the various negative impacts of aquaculture on indigenous bird and mammal populations. Aquacultural production practices that impact the quality and safety of aquacultural products are also discussed. Environmental contaminants, trace metals, organochlorines, microbial contaminants of shellfish, and algal toxins are considered in Chapter 12.

In Chapter 14, the author brings all the relevant information together to provide an outline of the steps that should go into planning an aquaculture venture with full consideration of the environment. Environmental impact assessments (EIA) and environmental impact statements (EIS) are discussed. The author provides a useful flowchart which shows the integration of EIA with other project activities in order to provide timely environmental information for improved planning and execution of aquaculture projects. Following such a format would avoid many of the past problems with large scale aquaculture developments. Examples of matrices and network analyses are also provided and should prove a useful tool, or template, for regulators and producers wishing to predict the possible environmental effects of aquaculture project development. The rest of the chapter discusses the possible mitigation methods for correcting environmental damage or engineering solutions to real-time contaminant problems.

One of the best attributes of this book is that the author has gone to the trouble to obtain the actual ranges of chemical and environmental parameters that must be taken into consideration in aquacultural practices. This makes the data presented much more useful to the reader concerned with the environmental regulation of aquaculture, whether producer or regulator. The presentation of well documented levels of pollution and contaminants brings a truth to the impact of aquaculture and forestalls some of the emotionalism seen in the past.

Another strong feature of this book is the international perspective taken by the author. The careful reader can follow the evolution of aquaculture in those countries with well established aquaculture industries and predict the course of events in other areas of the world. This may include the impacts of uncontrolled aquacultural development or the steady increase in the complexity of regulations controlling aquaculture development.

This book should provide a benchmark for the scientific treatment of the issues surrounding the controversy of the effects of aquaculture on the environment. The aquaculture industry, government regulators, and scientists will find it a welcome addition to their libraries.

Tanker Operations—A Handbook for the Ships Officer (Third Edition)
by G. S. Marton
Cornell Maritime Press (1992)
Centreville, Maryland. 313 pages. $35.00

Reviewed by
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Captain Marton's third edition of *Tanker Operations* is as good as the original. This edition is 105 pages longer than the first and 74 pages longer than the second with three new chapters. These new chapters are Chapter 2, "Petroleum and the Refining Process" by Robert Stewart; Chapter 12, "The Tanker and the Law" by Nicholas Blenkey; and Chapter 14, "Marine Vapor Control" by Mark Huber. For the most part, Captain Marton has managed to update his material by adding new illustrations and rewriting the text without changing the original intention of each chapter.

On a personal note, I was happy to see again the cutaway drawing of *Gulfking* in Figure 1–2. This was the ship I was sailing on when I read the original text for the first time. The caption under the *Gulfking* is the same but the reproduction quality of the diagram is improved.

As previously stated, each of the old chapters has been rewritten. The sailor's propensity to precede a topic with a harrowing personal experience (sea story), as a way to illustrate a point, has been removed in the rewriting. Presented, in its place, is a hypothetical case study with all personal references removed. Captain Marton has mastered the ability to be concise and descriptive. The first edition read like the old salt sharing his wisdom (and at times his opinions) with the uniformed landlubber. This third edition reads more like the conscientious professional simply and efficiently discussing his trade with the reader. The three contributors are to be commended for maintaining similarly easy reading while maintaining their own distinct styles.

There are some disappointing aspects of this book though. Some of the new illustrations were poorly chosen and located in such a manner that it is cumbersome to use. For example, three of the four illustrations in the section of Chapter 2 on "The Refining Process" were obscure, exterior photos of a refinery instead of drawings that detail a phase of the refining process. Additionally, in Chapter 4 on page 77, in the "Vapor Control Systems" section an illustration (Figure 5–3) is referenced in another chapter. This illustration shows how a typical vapor control system works, but it is located five pages away from the relevant text. The test surrounding Figure 5–3 is about "Removing the List" and "Hull Stresses." There is sufficient room for Figure 5–3 to have been placed on the bottom half of page 77, which is presently blank.

I was also disappointed at how little text there is on petroleum hazards, the proper use of the new CG-388, the proper use of the chemical Hazards Response Information System (CHRIS), the proper procedures for tank and confined space entry, and instructions on how to use modern atmospheric/vapor testing equipment. There is no mention of the importance of the difference between the readings from an explosimeter type combustible gas indicator and a tankscope type combustible gas indicator. The former measures vapor content in percent of the lower explosive limit; the latter measures vapor content by volume. That is an important difference!

I have the feeling there was a rush to get this edition to press. For example, Figure 2–13 is a sample of the 1982 edition of *CG-388, Chemical Data Guide for Bulk Shipment by Water*. The newest edition of CG-388 was available November 8, 1990. The model 2A Explosimeter, shown in Figure 9–19, seldom used on board modern tankers and should have been replaced with a picture of the model 260 Explosimeter. This newer model measures both oxygen level and the LEL of combustible gases at the same time and has a battery operated pump. I would have preferred delaying the publication of this edition a year to include the much awaited Benzene Standard issued October 17, 1991.

In spite of the deficiencies, this book does achieve its goals, as stated in the "Preface." Those goals are for the book to be an introductory text for new or prospective officers, to be of interest and practical value to more experienced officers, and to be used as a reference by tanker charters and owners. I use this book as the primary text in two courses on tanker operations and as the secondary reference text in a course on marine safety. I recommend it to everyone whose work is even remotely related to tankers, selling petroleum, tankship chartering, or oil spill prevention.

UPCOMING
MTS JOURNAL ISSUES

Fall 1993
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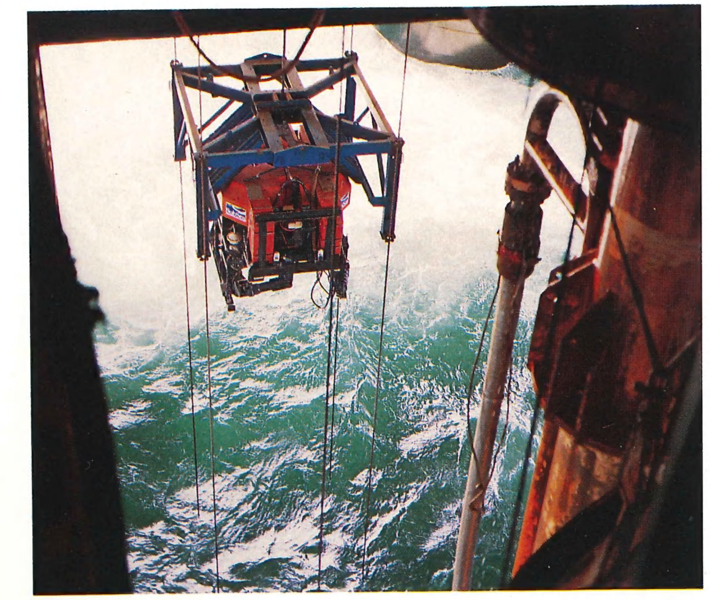

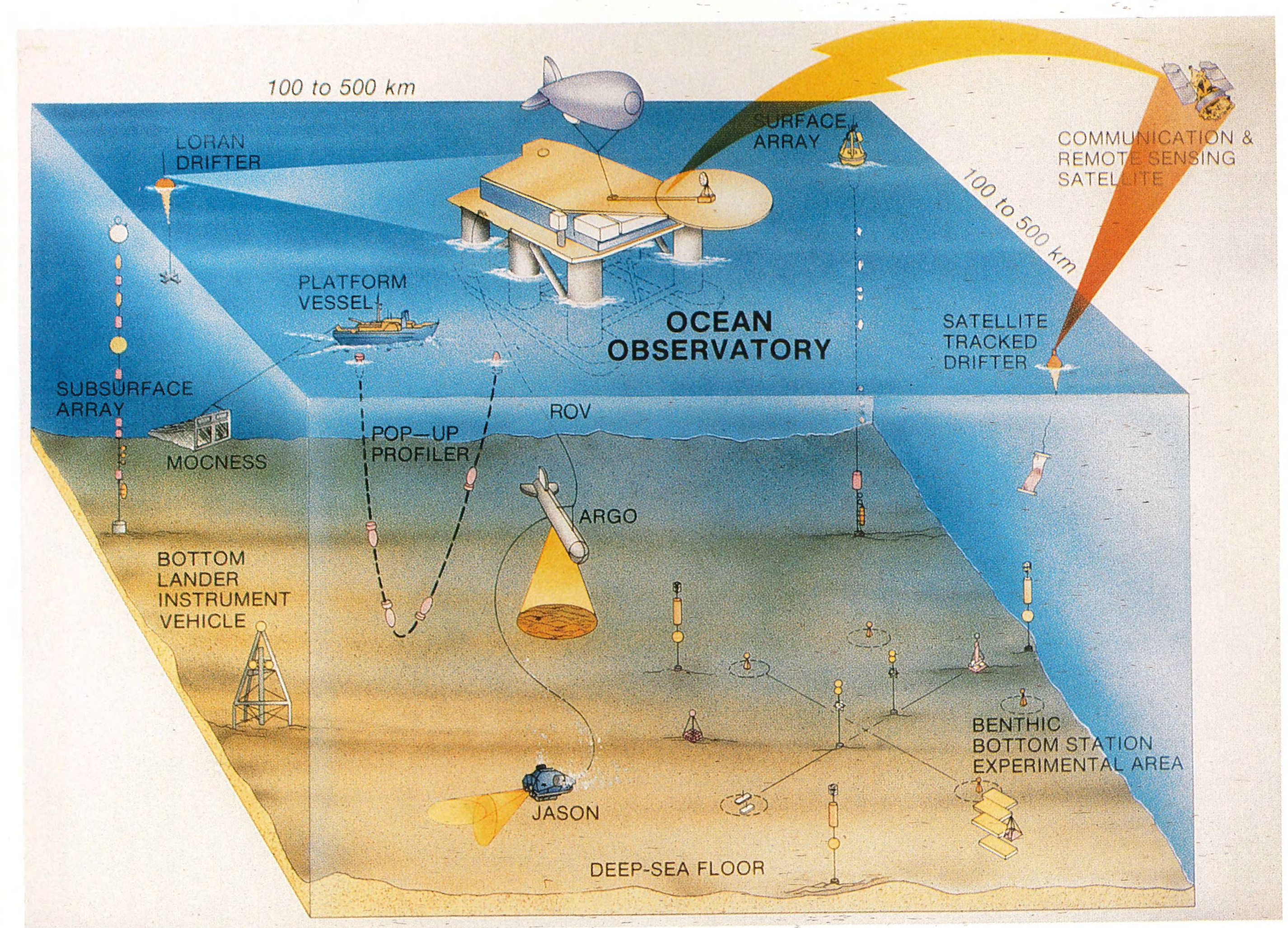

Inside Back Cover
Top left: John Shaw drilling rig on location in the Bruce field in the North Sea. Photo: Courtesy of British Petroleum. *Top right:* On board BP's drilling rig Ocean Alliance on site in the North Sea. Photo: Courtesy of British Petroleum. *Bottom:* Conceptualization of the Deep-Sea Observatory located in the middle of the North Atlantic Ocean in direct communication with shore-based locations and the manned-space station and able to receive real-time satellite imagery for processing and interpretation in aid of the ongoing research activities. Diagram: Courtesy of the Deep-Sea Observatory Organizing Committee.

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